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TRACKING AND DATA RELAY SATELLITE SYSTEM CONFIGURATION AND TRADEOFF STUDY

Volume 1. TDRS System Summary



HUGHES AIRCRAFT COMPANY
SPACE AND COMMUNICATIONS GROUP
El Segundo, California

29 September 1972
Part I Final Report

Prepared for
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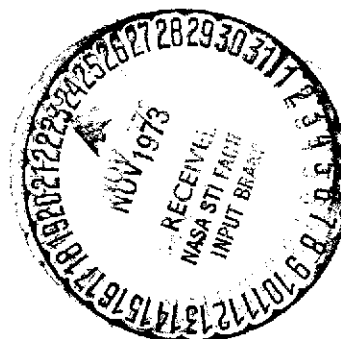
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<p>16. Abstract A Tracking and Data Relay Satellite System (TDRSS) concept for service of low and medium data rate user spacecraft has been defined. The TDRS system uses two geosynchronous dual spin satellites compatible with Delta 2914 to provide command, tracking, and telemetry service between multiple low earth orbiting users and a centrally located ground station. The low data rate user service capability via each TDRS is as follows:</p> <p>Forward link at UHF: voice to one user, commands to 20 users (sequential), range and range rate service.</p> <p>Return link at VHF: voice from one user, data from 20 users (simultaneous), range and range rate return signals.</p> <p>The medium data rate user service via each TDRS is as follows:</p> <p>Forward link at S band: voice or command and tracking signals to one user.</p> <p>Return link at S band: voice, data and tracking signals from one user "order wire" for high priority service requests (implemented with an earth coverage antenna).</p>			
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1. INTRODUCTION

The objective of the Hughes Tracking and Data Relay Satellite System (TDRSS) study is to identify an optimum approach for a TDRSS by use of dual spin, geosynchronous tracking and data relay satellites, and to define the performance parameters of all elements of the system. The study has been divided into two parts: Part I, a 7 month effort to develop a TDRSS concept with service for medium and low data rate users with a TDRS compatible with the Delta 2914 performance and payload envelope constraints; Part II, a 5 month effort, to implement design and cost changes in the major TDRSS elements to provide an increased telecommunications capability (service of high data rate users) and to explore the performance potential of TDRSS launched by Atlas class vehicles and the Space Shuttle.

Part I of the study has been completed. The baseline system concept and tradeoffs that led to the system definition are described in this Part I final report. Applicable experience from current commercial and military space programs has been utilized throughout the study to arrive at an overall system technical approach that stresses simplicity, economy, flexibility, and ease of operations. For example, maximum use of existing Goddard Space Flight Center network control and scheduling, orbit determination, and data processing capabilities has been planned. The TDRS design makes use of a maximum of flight proven design concepts and equipment.

This report is organized in five volumes:

Volume 1	TDRS System Summary
Volume 2	Cost Estimate for TDRSS Part I Baseline Configuration
Volume 3	TDRSS Configuration and Data Summary
Volume 4	TDRS System Operation and Control and Telecommunications Service System
Volume 5	TDRS Spacecraft Design

A complete table of contents of all five volumes has been included.

This volume contains an introduction to the system concept and a brief system performance and configuration summary.

2. SYSTEM CONCEPT

The TDRSS concept uses two geostationary satellites to provide relay links for command, tracking, and telemetry between multiple low earth-orbiting user satellites and a centrally located ground station, as shown in Figure 1, making possible nearly continuous reception of data in real time.

The TDRSS comprises the following major elements:

- GSFC communication control and processing facility
- TDRSS ground station
- TDRS control center
- (Two) TDR Satellites
- User spacecraft equipment

The communication links from the ground station to the user are defined as forward links, and the links from the user spacecraft to the ground station are defined as return links.

The forward links contain user command, tracking signals and voice transmissions, whereas the return links contain the user telemetry, return tracking signal, and voice.

The users are categorized as low data rate (LDR), medium data rate (MDR), and high data rate (HDR) according to their telemetry rates.

2.1 KEY GROUND RULES

The key ground rules for the TDRSs as contractually defined are:

- Dual spin configuration
- Delta 2914 launch vehicle payload and fairing constraints
- Minimum lifetime of 5 years

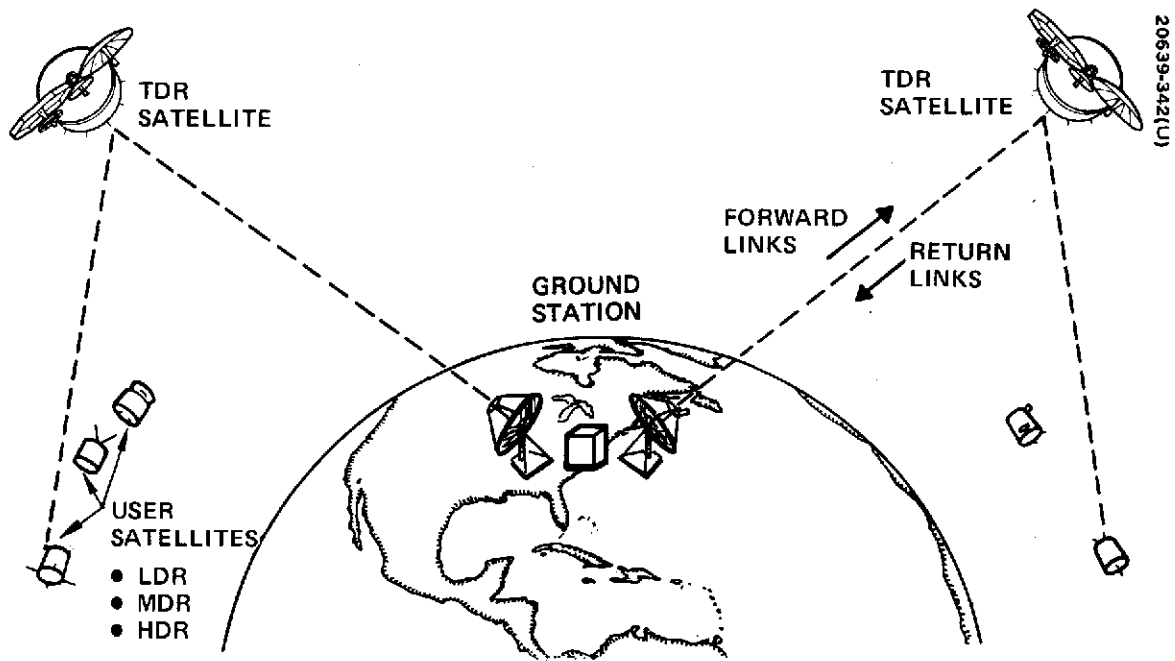


Figure 1. TDRSS Concept

- Telecommunication service by each TDRS
 - At least 20 LDR users
 - At least 1 MDR user
 - Two-way voice for manned users

During the current study effort, discussions with the GSFC Program Office have led to the conclusion that the following additional ground rules, although not contractually required, are essential for a viable system concept:

- MDR service compatible with Space Shuttle
- Flux densities for forward links compatible with CCIR regulations
- Maximum use of proven subsystems and technology

These ground rules have been observed throughout the analysis and design.

2.2 TELECOMMUNICATION SERVICE VIA EACH TDRS

Each TDRS provides identical telecommunication service. Thus the total service available from the system will be twice that shown in Table 1.

The LDR service forward link uses the 400.5 to 401.5 mHz UHF band and the return link uses the 136 to 138 MHz VHF band compatible with current NASA ground stations. Both the forward and return links are implemented with broad coverage (30 degree cone) antennas. LDR service provides one two-way voice link per relay and a telemetry, tracking, and command service link for at least 20 LDR users per TDRS. The commands are transmitted sequentially, with the command sequence defined by the scheduled LDR user priorities. Data, however, are received from all LDR users simultaneously. Tracking is accomplished simultaneously with command and telemetry.

MDR service forward and return links use an S band and are implemented with a steerable narrowbeam antenna. MDR service is limited to one MDR user at a time per TDRS. Since this link will likely be time-shared by several MDR users, an order wire capability is implemented to permit a service request signal from a high priority user to the ground station.

For the worst case (end of life, maximum eclipse duration), the power limitations of the TDRS restrict the use of the voice service alternatives to one at a time from each TDRS, with the following duty cycles for the forward link: UHF, 25 percent and S band, 50 percent. The return links are available continuously.

TABLE 1. AVAILABLE TDRS SERVICE

LDR	
•	Forward link — UHF
•	• Voice to one user
•	• Commands to 20 users (sequential)
•	• Range and range rate signals
•	Return link — VHF
•	• Voice from one user
•	• Data from 20 users (simultaneous)
•	• Range and range rate return signals
MDR	
•	Forward link — S band
•	• Voice, command/data, and tracking signals to one user
•	Return link — S band
•	• Voice or data and tracking signals from one user
•	• "Order wire" for high priority service requests

2.3 TDR SPACECRAFT

An artist's concept of the TDRS is shown in Figure 2. The dual-spin spacecraft configuration is compatible with the Delta 2914 performance capability of 680.4 kg* and with the payload fairing constraints. Proven subsystems and technology have been used extensively in developing the baseline design.

Of particular interest is the antenna subsystem, which consists of:

- 1) Deployable 3.96 meter diameter VHF antenna for LDR return link (fixed)
- 2) Deployable 1.46 meter diameter UHF antenna for LDR forward link (deployed inside the VHF antenna) (fixed)

*Excluding payload attach fitting.

- 3) Deployable 3.82 meter diameter S band antenna for MDR forward and return links (gimbaled)
- 4) S band order wire antenna (fixed)
- 5) 1.43 meter diameter Ku band antenna for TDRS-to-ground station link (gimbaled)
- 6) Two earth coverage Ku band horn antennas for the ground station-to-TDRS link (fixed)
- 7) Whip-type omni antennas for backup telemetry and command links for the TDRS

The deployable antennas have been configured by Radiation Incorporated, compatible with their studies for the NASA Langley Research Center.

The S band and the large Ku band antennas are installed on two-axis gimbals that provide a pointing capability over the 30 degree cone.

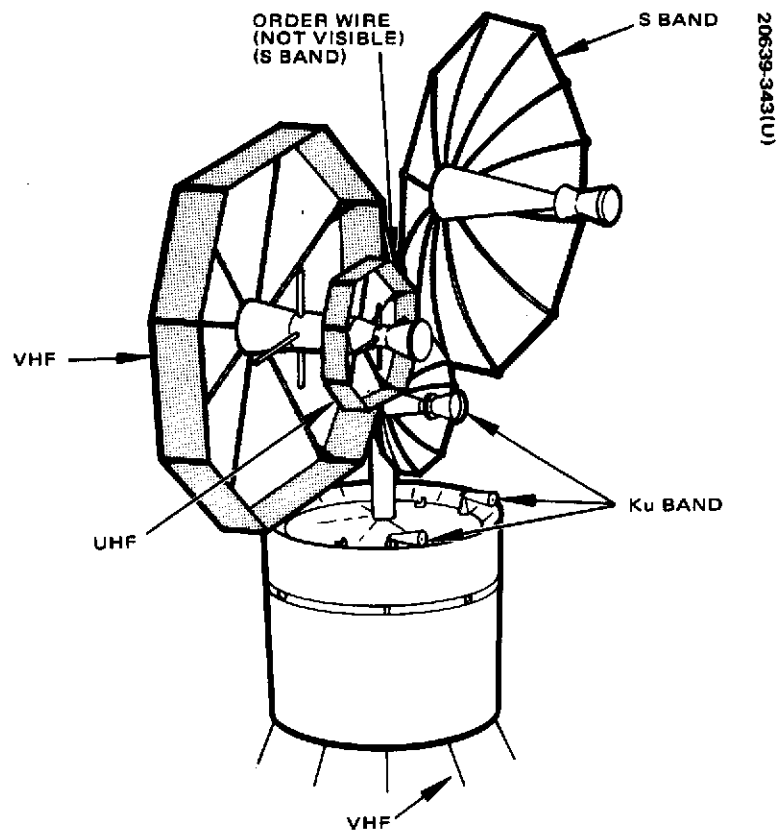


Figure 2. TDR Spacecraft Configuration

3. TELECOMMUNICATION SERVICES

The user spacecraft visibility, RFI geometry, and telecommunication service link design and performance is summarized in the following subsections. The attainable bit rates in all links depend critically on the assumed user EIRP, the bit error rate probabilities, and, for LDR service, on the RFI environment. Thus, particular attention should be given to the assumptions listed for each performance curve. An attempt has been made in all cases to employ realistic assumptions.

3.1 USER SYSTEM VISIBILITY BY TDRSS

User visibility by the TDRSS is shown in Figure 3. The ordinate of the figure represents a ratio of the surface area visible to two TDRSs to the total surface area of a sphere at the user altitude. Such a ratio will usually not represent the user visibility during any single orbit; however, it is a good quantitative characterization of the average user visibility.

Note that for orbital altitudes above 5000 km a user will be outside the LDR antenna coverage pattern (30 degree cone) part of the time, and user visibility will decrease with increases in orbital altitude above this limit.

3.2 LDR SERVICE

The low data rate link segments between a TDRS and user spacecraft employ broad coverage antennas giving 30 degree conical coverage. Thus, user spacecraft with orbital altitudes up to 5000 km can be accommodated.

The design of the low data rate service and signal processing accommodates a minimum of 20 unmanned users per TDRS for both the forward and return links. The forward link is timed-shared, thus only one user can be commanded at a time per TDRS. However, there is no system limit to the number of users to which commands can be sent, since each command will have a user identifying prefix that activates the command decoder of the intended user.

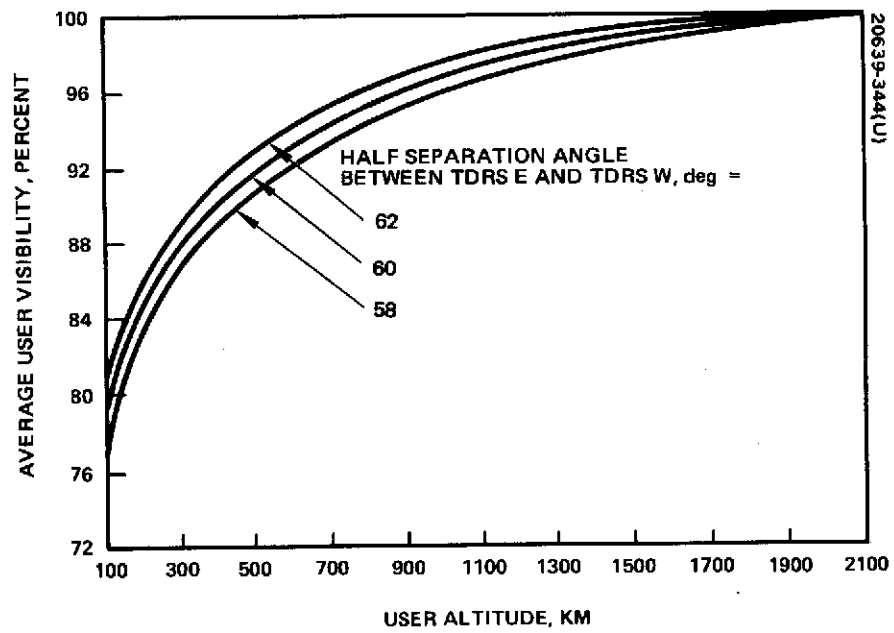


Figure 3. User Visibility by TDRS

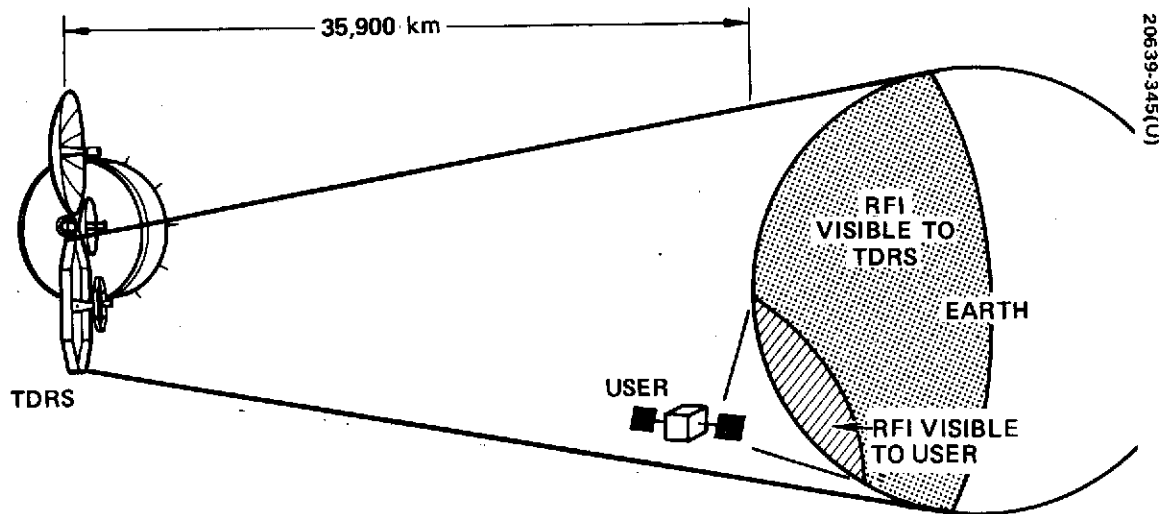


Figure 4. RFI Geometry

3.2.1 RFI Geometry

Both forward and return links are affected by RFI, and analysis has shown that this interference will probably be the limiting factor. The geometry associated with RFI is illustrated in Figure 4. Each TDRS sees more than 40 percent of the earth's surface, and the LDR return link antenna collects noise power from all emitters in the visible region. The RFI noise level seen by each TDRS will vary slowly, since each TDRS always views the same large region. A low altitude user spacecraft views a considerably smaller portion of the earth's surface, and therefore is affected by a lesser number of RFI emitters, but is much closer to these emitters, effectively receiving higher power per emitter than the TDRS. A user, orbiting over high and low RFI emitting regions, experiences a wide range of RFI variations. The parameter chosen to quantify RFI is the average spectral density, η_{RFI} at the TDRS or user receiver.

The number of users transmitting in the common spectrum also has a significant effect on the capacity. However, the exact number of users that may use the return link cannot be identified. It is the nature of the selected wideband code division multiplex (CDM) approach that if a total of 40 users are successfully transmitting return telemetry via the two TDRSs, then 41 or maybe even 50 could also successfully return telemetry.

3.2.2 Forward Link

The low data rate service provides two forward links, one of which will be used primarily for command of user spacecraft, and the other primarily for voice communication with a manned user. These two separate channels have an identical design to provide greater system flexibility and spaceborne electronics reliability and provide a high capability failure mode. Due to TDRS power limitations, the voice channel is restricted to 25 percent usage during eclipse periods. Both the command and voice services discussed below are provided within a 30 degree conical coverage pattern of the TDRS UHF antenna.

The major selected signaling and multiplexing techniques are:

- 1) PN coding for both user commands and voice
- 2) Code division multiplexing of user commands and voice

The use of PN coding is the major signal design characteristic and allows four objectives to be accomplished:

- 1) Commands and voice can be code division multiplexed.
- 2) Multipath interference is reduced due to the spectrum spreading.
- 3) Earth-incident flux density is reduced to meet CCIR requirements.
- 4) Range measurement accuracy is improved.

3.2.2.1 Command Channel

The user command channel will be time-shared; that is, only one user can be commanded at a time. However, commands may be sent to many users within a period of 1 minute. All users will receive the TDRS transmitted RF signal; thus each command will have a prefix which will activate the command decoder of the intended user.

Other operational features include:

- | | |
|-------------------------------|--|
| 1) Automatic user acquisition | User available for command shortly after becoming visible. |
| 2) Time shared link | Requires synchronized sequencing of user commands. |
| 3) Fixed timing | <ul style="list-style-type: none">• User receivers can be standardized• Ground operations and equipment can be simplified |
| 4) Variable format | Number of bits and their significance in a user command can be different for every user if desired, i. e., command format flexibility. |

Analysis of the low data rate links and a study of ground emitters has revealed that RFI is most likely the limiting factor in these links. Figure 5 shows how the bit rate is limited by RFI.

The following two examples illustrate the forward link RFI problem:

- | | |
|--|--------|
| 1) Assuming a user 500 km above a 10 watt ground transmitter with: | |
| • Ground transmitter EIRP toward user | 10 dBw |
| • User spacecraft antenna gain towards the ground transmitter | 0 dB |

The equivalent noise density at the user receiver in the 1 MHz signal bandwidth is approximately -188 dBw/Hz. In such a case, the maximum possible command rate, as seen from Figure 5, is approximately 100 bps.

- | | |
|---|--|
| 2) Assuming only one change from the preceding example, namely, a directional user antenna with a gain of 7 dB towards the TDRS and a gain of 0 dB towards the ground transmitter, a maximum command bit rate of 750 bps is possible. | |
|---|--|

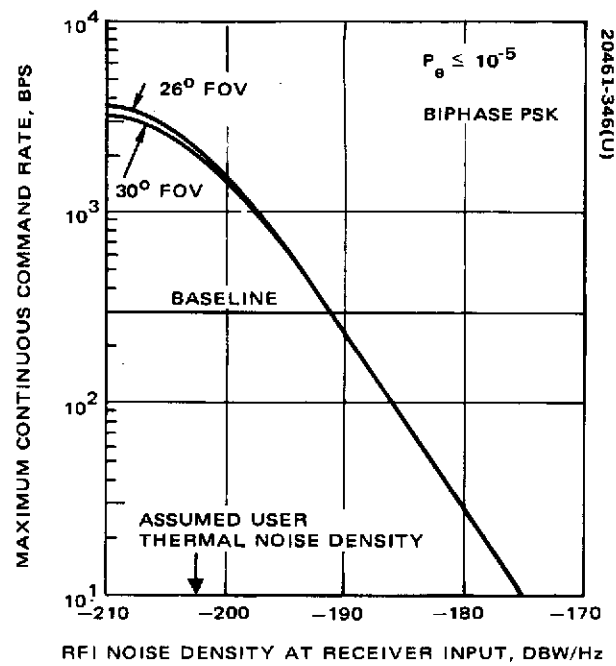


Figure 5. Low Data Rate Forward Link Capability

Note also that if the user spacecraft shields its antenna from the RFI sources it is equivalent to implementing a directional antenna.

3.2.2.2 Voice Channel

The voice channel employs delta modulation to convert the analog voice signal to a binary wave form. The baseline bit rate is 9.6 Kbps, resulting in high quality transmission. The bit energy-to-noise density is shown in Figure 6 as a function of RFI density. It may be noted that the use of convolutional encoding will allow operation at higher levels of RFI and will probably be required.

3.2.2.3 Signal Parameters

The signal parameters selected for the baseline design are:

- | | |
|--|----------------|
| 1) Chip (PN code symbol) rate | 614 kchips/sec |
| 2) Command bit rate | 300 bps |
| 3) Command code length | 2048 |
| 4) Voice bit rate | 9.6 Kbps |
| 5) Voice code length with rate
1/2 convolutional encoding | 32 |

The frequency band chosen is the allocated UHF band 400.5 to 401.5 MHz. This band was selected over a VHF band because 1) more bandwidth is available, 2) RFI is expected to be smaller, and 3) it is a currently internationally allocated band for space use.

3.2.3 Return Link

The LDR return link allows simultaneous reception from up to at least 20 telemetry transmitting users and one voice user per TDRS. The telemetry channel and voice channel occupy separate frequency bands at 136 to 137 MHz and 137 to 138 MHz, respectively. As with the forward link, the return link service is provided within a 30 degree field of view from the TDRS.

The low data rate return link capability per user is a function of the number of active users, their EIRP, and the multipath and RFI environment. Figure 7 shows the telemetry link capability per user versus the user EIRP, with the RFI noise density as a parameter. The curves are plotted over a representative set of system parameters and include allocations for various degradations, but do not assume worst case conditions or a link design margin. For a user EIRP of 4 dBw, in the absence of RFI, the system is limited to about 2.5 kbps, as can be seen from the upper curve. With a more advanced user communication terminal with greater EIRP, the link is limited to 4 Kbps.

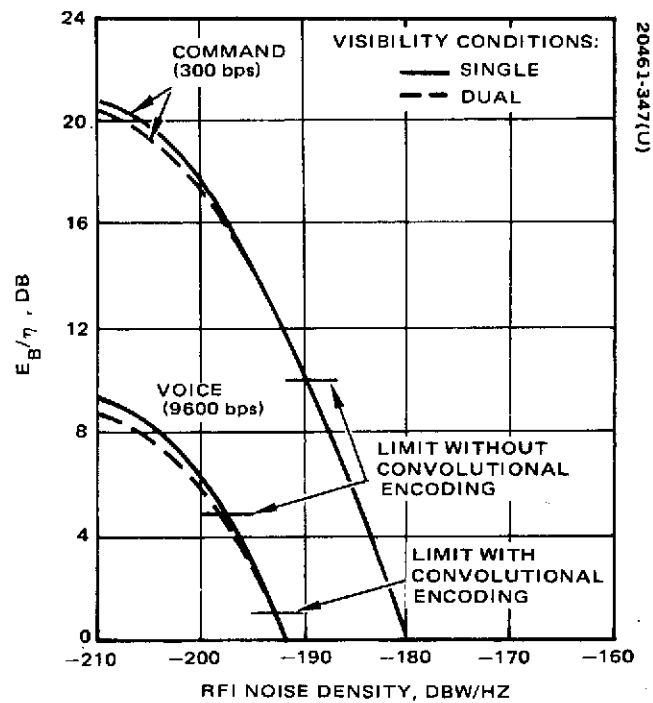


Figure 6. UHF Forward Link Signal Concepts; 26 Degrees FOV

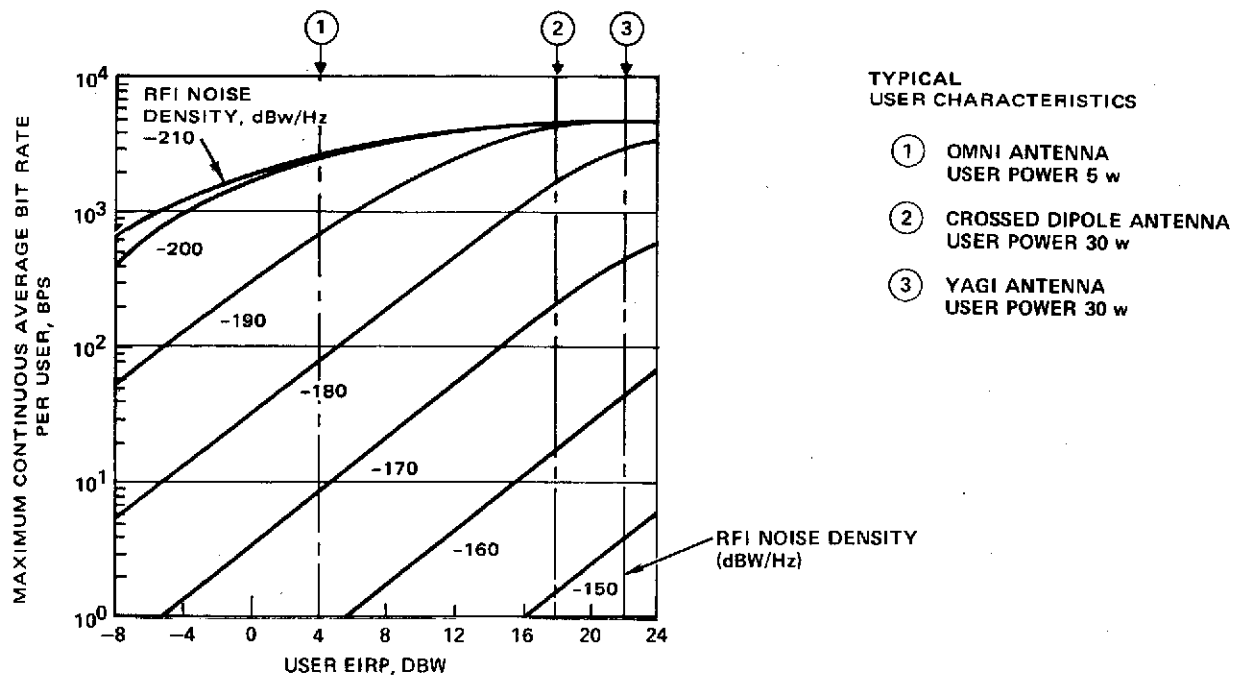


Figure 7. Low Data Rate Return Link Capability

The RFI noise density is that which appears at the receiver input. Thus calculated or measured earth RFI noise densities have to be corrected for antenna gains or RFI suppression prior to use of this figure. The higher values of user EIRP may be required to provide desired data capacity in presence of current RFI estimates. The assumptions which were used in producing Figure 7 are listed in Table 2.

Signal Parameters. The selected signaling and multiplexing techniques are:

- 1) User telemetry and voice occupy separate frequency bands

Telemetry	136 to 137 MHz
Voice	137 to 138 MHz

TABLE 2. LOW DATA RATE RETURN TELEMETRY CHANNEL ASSUMPTIONS

- 20 visible users
- Average received power of other users 4 dB more than desired user
- Average relative multipath per user, -6 dB*
- RFI noise density measured at TDRS receiver input
- TDRS G/T \geq -16 dB/K (edge of coverage)
- Polarization combining 0.5 dB from theoretical
- PN correlator/convolutional decoder operation 2 dB from theoretical
- Ground link signal-to-noise ratio, 16.5 dB
- Bit error rate, $\leq 10^{-5}$
- RF bandwidth, 1 MHz

*The multipath assumption is that for multiple users, the total received multipath power from all users is 6 dB less than the total received direct power. This may also be interpreted as follows: on the average, each user's multipath power received by the TDRS is 6 dB less than its direct power.

- 2) User telemetry will be PN code modulated to occupy the entire 1 MHz band.
- 3) Voice signal will PN code modulated as required to meet CCIR requirements.
- 4) Simultaneous multiple user telemetry signals are code division multiplexed in the 136 to 137 MHz channel; thus, each user's PN code will be different.
- 5) Convolutional encoding will be employed on user telemetry for bit error correction; link quality is improved significantly with this technique.

The baseline approach assumes that the return bit rate is standardized for all users but this is not a system requirement. With this standardization the baseline parameters are as follows:

- | | |
|--------------------------------------|----------------|
| 1) Telemetry bit rate | 1200 bps |
| 2) Convolutional encoding rate | 1/2 |
| 3) PN code length | 511 |
| 4) Chip rate | 1.22 Mcips/sec |
| 5) Voice bit rate (delta modulation) | 19.2 Kbps |

3.2.4 User Tracking

Tracking refers to range and range rate measurements from which user orbital parameters can be derived. The geometry shown in Figure 8 shows the four segments that are involved in the required two-way transmission. Thus, four transmitters and four receivers are active in this process; two of each are on the TDRS.

Range rate measurement requires the determination of total doppler shift at the ground station, and thus requires phase coherence of the three oscillators in the respective terminals as shown. Measurement of range requires time delay determination in the round trip signal transmission; thus timing synchronization is required. The use of PN codes in the low data rate services automatically provides this synchronization at both user and ground station.

Due to the PN code signaling, user spacecraft receivers automatically acquire and synchronize to the signal transmitted from a TDRS. After the brief acquisition period, range and range rate measurements can be made. However, the user's transmitter must be turned on, and the return signal acquired at the ground station. A particular operational advantage of the signaling concepts used here is that both range and range measurements can

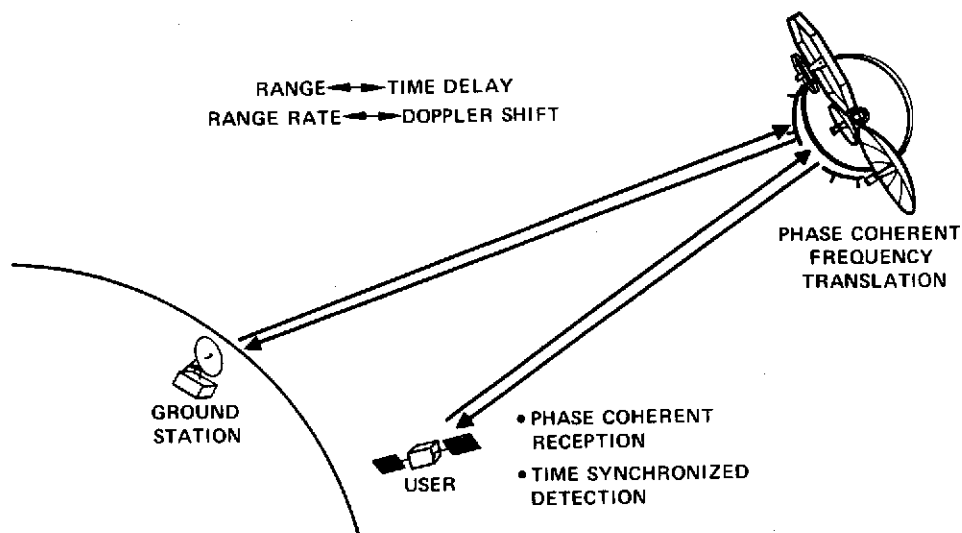


Figure 8. User Tracking

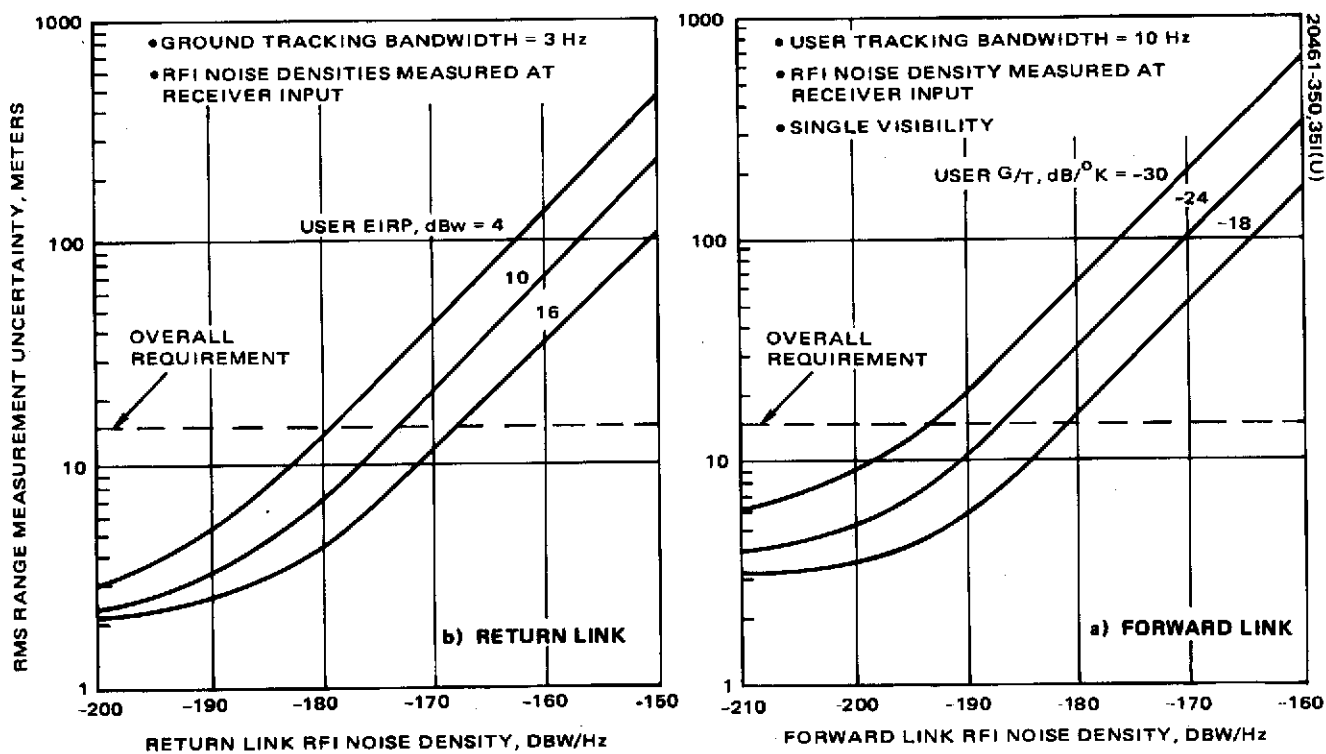


Figure 9. RMS Range Measurement Uncertainty

be made simultaneous with telemetry reception, and no forward link commands are required.

The performance limit of the range measurement system is shown in Figure 9 as a function of return link RFI noise density. The total rms uncertainty is the sum of the forward and return link rms uncertainties.

The accuracy of range measurements is limited by thermal noise in the receivers and instability of the three oscillators in the round trip transmission. It can be seen that the low data rate system requirement of 15 meters random uncertainty can be satisfied if RFI power is small for the forward link and less than about -180 dBw/Hz in the return link.

3.3 MEDIUM DATA RATE (MDR) SERVICE

The medium data rate service requires a high gain antenna on each TDRS. This antenna has the angular freedom to follow user spacecraft in orbits with altitudes up to 5000 km. Because of the narrowbeam antenna pattern, two-way communication is possible with only one user spacecraft at a time via each TDRS.

The TDRS repeater has been designed to accommodate a 1 Mbps data rate on the return link.

The wideband (10 MHz) phase coherent repeater allows range and range rate measurements to be made by almost any method preferred by the user. In addition, capability is provided to position the transmit (forward link) 10 MHz band, anywhere in the 2035 to 2120 MHz frequency range and to position the receiver (return link) 10 MHz band anywhere in the 2200 to 2300 MHz range.

The S band transmitter operates at two power levels resulting in two EIRP levels: 47 and 41 dBw. The former is restricted to part-time use due to TDRS power limitations.

The high power mode will allow transmission of 22 Kbps delta modulated voice on the forward link, to accommodate 19.6 Kbps delta modulated voice and 2 Kbps data. The TDRS antenna and receiver design provides for a 100 Kbps combination of voice and data on the return link from a manned user with an omni antenna and 100 watts of RF power.

Flux density calculations indicate that the forward link spectrum must be spread prior to transmission from the ground complex in order to meet CCIR requirements, and probably the return link spectrum will also require spreading.

3.3.1 Forward Link

As mentioned above, each TDRS has two transmitter power levels for the MDR forward link. In addition to this variation, the user's antenna gain

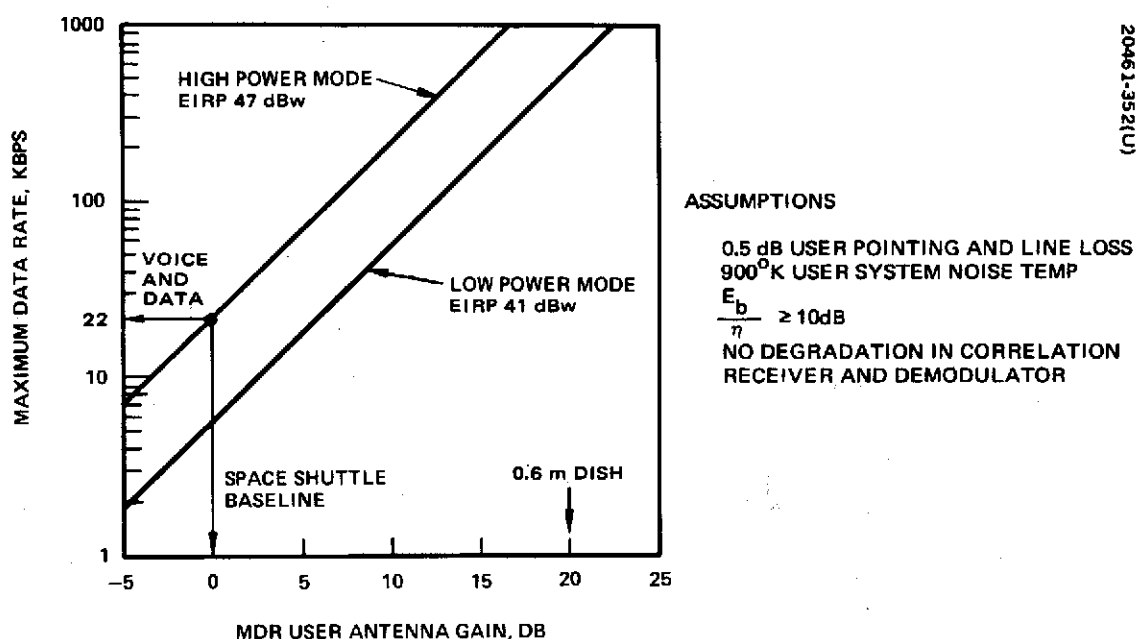


Figure 10. Medium Data Rate Forward Link Capability

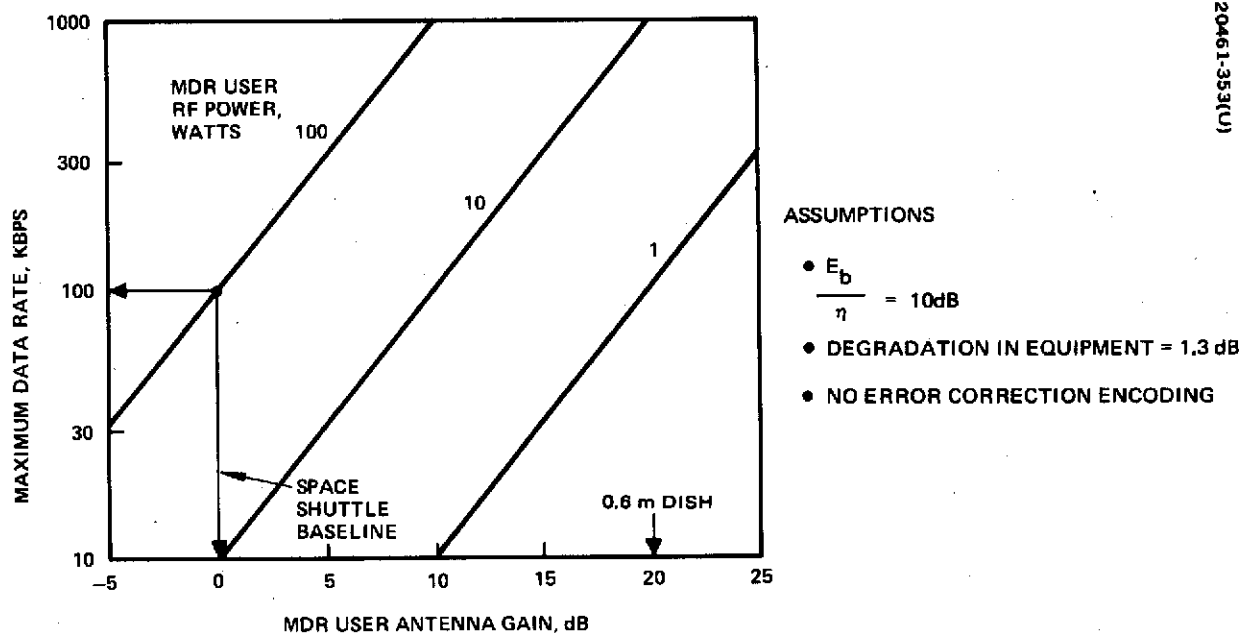


Figure 11. Medium Data Rate Return Link Capability

and receiver quality determine the data rate capacity of the medium data rate forward links. Figure 10 shows the maximum possible forward link data rate, assuming no error correction encoding and a receiver system noise temperature of 800 K.

The high power level was determined by the requirement to transmit a 22 Kbps digital voice plus data signal to the Space Shuttle with a 0 dB gain antenna. It can be seen that in the low power mode bit rates greater than 1 Kbps are possible with antenna gains less than 0 dB. Note that even a 20 dB gain requires a relatively small antenna.

3.3.2 Return Link

The medium data rate return link capability is determined by the TDRS G/T ratio and user EIRP. The TDRS G/T ratio (10.5 dB/K considering receiver noise only) was determined by the requirement to receive data plus voice (approximately 100 Kbps total) from the Space Shuttle with an EIRP of 20 dBw (100 watts). Figure 11 relates the maximum possible data rate to user power and antenna gain assuming no error correction encoding. The use of error correction encoding would increase the maximum data rate of both the forward and return links by a factor of up to 7.

The return link system requirement of 1 Mbps can be achieved with a user EIRP of 30 dBw, which might consist of a 20 dB antenna gain and 10 watts of RF power.

3.3.3 Tracking

The 10 MHz bandwidth will allow both the range and range rate measurement accuracy requirements to be met with sufficient ground oscillator quality and user communication equipment capability.

3.4 ORDER WIRE

An S band antenna has been provided which has a gain of 13.2 dB or greater for orbital altitudes up to 550 km. The repeater channel has been designed so that approximately 1 Kbps can be transmitted to the Ground Station at any time by a manned spacecraft with an omni antenna and 100 watts of radiated RF power. Thus, a request can be made by such a spacecraft for MDR service accompanied by priority level data.

The channel bandwidth is 1 MHz, centered at 2201 MHz, so that if the manned spacecraft can provide greater EIRP, more data, or even voice, could be relayed via this service.

3.5 S BAND TRANSPONDER

A turnaround S band transponder has been provided to allow accurate TDRS range measurements. The bandwidth is 8 MHz centered at 2290 for

receive and 2045 for transmit. The transmitted EIRP is 18 dBw. This transponder will allow trilateration techniques such as those currently being designed for the Synchronous Meteorological Satellite.

3.6 VOICE SERVICE

Voice service can be provided by both an independent LDR voice service (UHF forward/VHF return) and the MDR service (S band) via either TDRS.

The LDR voice channel employs delta modulation to convert the analog voice signal to a binary wave form and convolutional encoding to allow operation at high levels of RFI. The forward link bit rate is 9.6 Kbps, and the return link bit rate is 19.2 Kbps, providing high quality transmission. The MDR bit rate is 19.2 Kbps for both forward and return links.

4. TDRSS OPERATIONS AND CONTROL

The TDRSS operations and control involve three major functions:

- TDRS launch and orbital deployment
- TDRS on-orbit control
- TDRSS telecommunication service operations.

Each of these topics will be discussed briefly in the following subsections.

4.1 TDRS ORBIT INSERTION PROFILE

The TDRS launch and orbit insertion sequence is similar to that used for other synchronous satellites, e. g., Intelsat IV. The key events in the mission are shown in Figure 12.

During the transfer orbit, the TDRS telemetry and command will be accomplished with the VHF backup TT&C system. The satellite will be reoriented in the apogee motor firing attitude prior to the second apogee. Depending on the launch dispersions, the second or third apogee will be selected for the apogee motor firing (to achieve a favorable drift toward station after apogee injection).

At the final station orbit, trim maneuvers to circulate and synchronize the orbit will be performed. The antenna deployment will be performed at the final station after the orbit trim maneuvers are completed.

A final orbit inclination of 7 degrees is selected as a compromise between spacecraft mass, inclination biasing requirements, and user coverage.

4.2 TDRS ON-ORBIT CONTROL

There are two systems for TDRS telemetry and command — K band and VHF. The K band system is prime and the VHF system, which employs an omni antenna on the TDRS, is for backup. The backup system is compatible with the Goddard range and range rate (GRARR) system. A schematic of the TDRSS TT&C concept is shown in Figure 13.

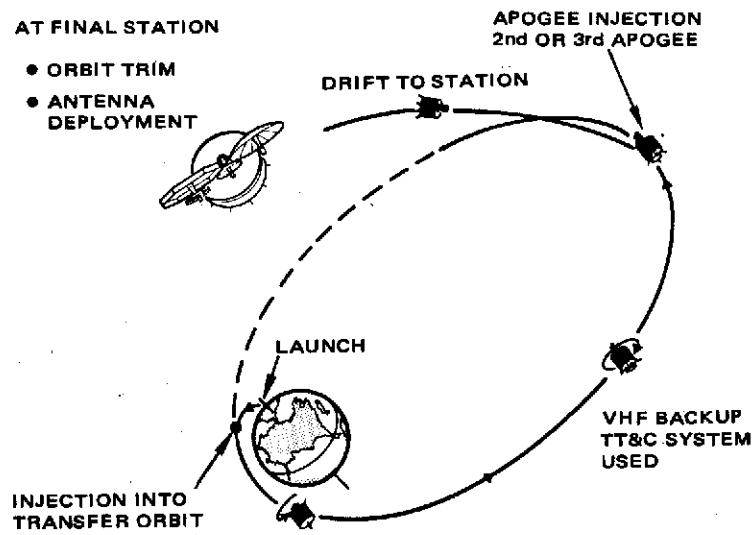


Figure 12. TDRS Orbit Insertion Profile

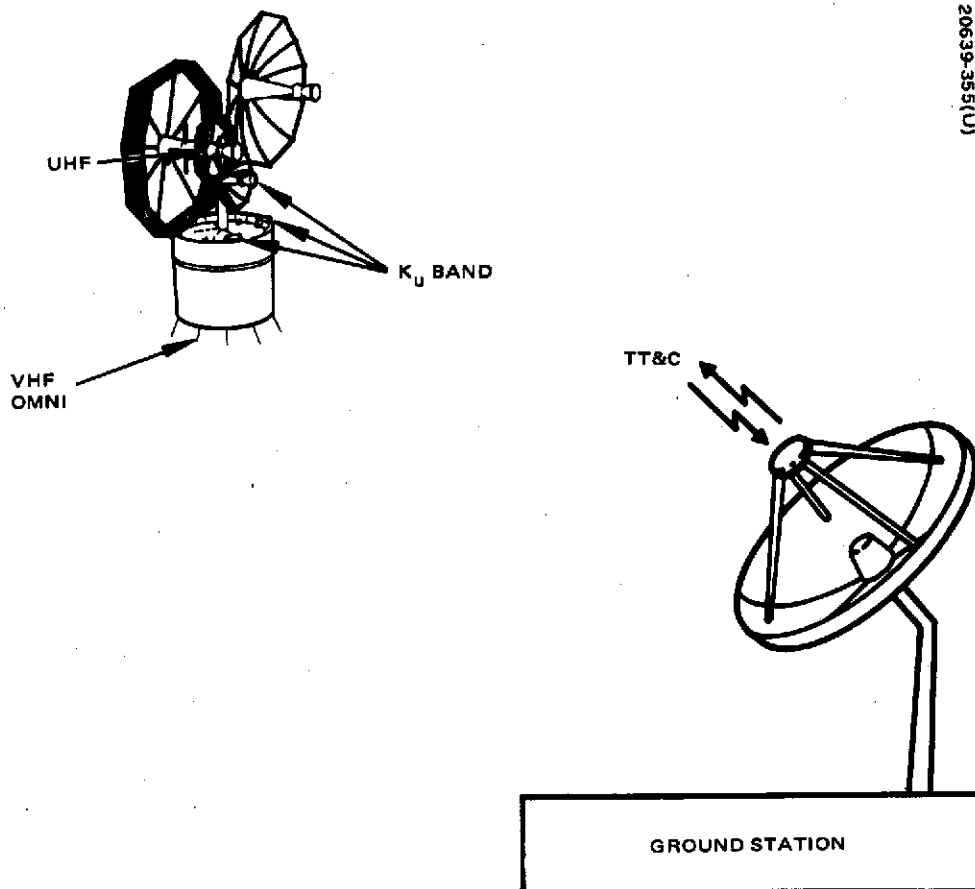


Figure 13. TDRS Telemetry and Command Concept

TDRS tracking is accomplished using the LDR forward link. A signal is continuously sent to each TDRS on this link via the K band system. Each TDRS repeats the signal at UHF via the broad coverage antenna. A relatively low gain UHF antenna can be used to receive these signals at the ground station, where they are processed to provide range and range rate measurements for the TDRS.

The on-orbit control operations for the TDRS are:

- East-west stationkeeping
- Attitude maneuvers
- S band and K band antenna pointing
- TDRS repeater channel settings

The frequency of east-west stationkeeping maneuvers is approximately one maneuver every 100 days and the frequency of the attitude maneuvers is one maneuver every 2 days. The satellite has sufficient angular momentum so that antenna pointing will not require any attitude correction maneuvers. The stationkeeping and attitude correction maneuvers do not require an interruption of the telecommunication service to the users.

4.3 LDR USER SERVICE PROFILE

A typical sequence for LDR service to a user spacecraft is illustrated in Figure 14. An explanation of this sequence will aid in understanding the LDR control functions described in the following pages.

Position 1 represents the end of an occultation period during which TDRS E was not visible to the user spacecraft. The user receiver is set to the TDRS E code, and after a brief period (not exceeding 60 seconds), the user's receiver is automatically synchronized to the signal transmitted from TDRS E. Following this signal acquisition, the user spacecraft is ready to receive commands. If the user is transmitting, a ground receiver corresponding to that user's coded telemetry signal will acquire the user's signal in a brief period, less than 60 seconds, after which range and range rate measurements may be made simultaneously with telemetry data reception.

In position 2 the user is visible to both spacecraft, and a command is sent to the user via TDRS E to change his receiver code to correspond to the signal from TDRS W. This change is followed by automatic acquisition of the signal from TDRS W. Only two receiver codes are required for all users. Finally, in position 4 before occultation, the user is commanded to change his receiver code back to TDRS E in preparation for communication following occultation.

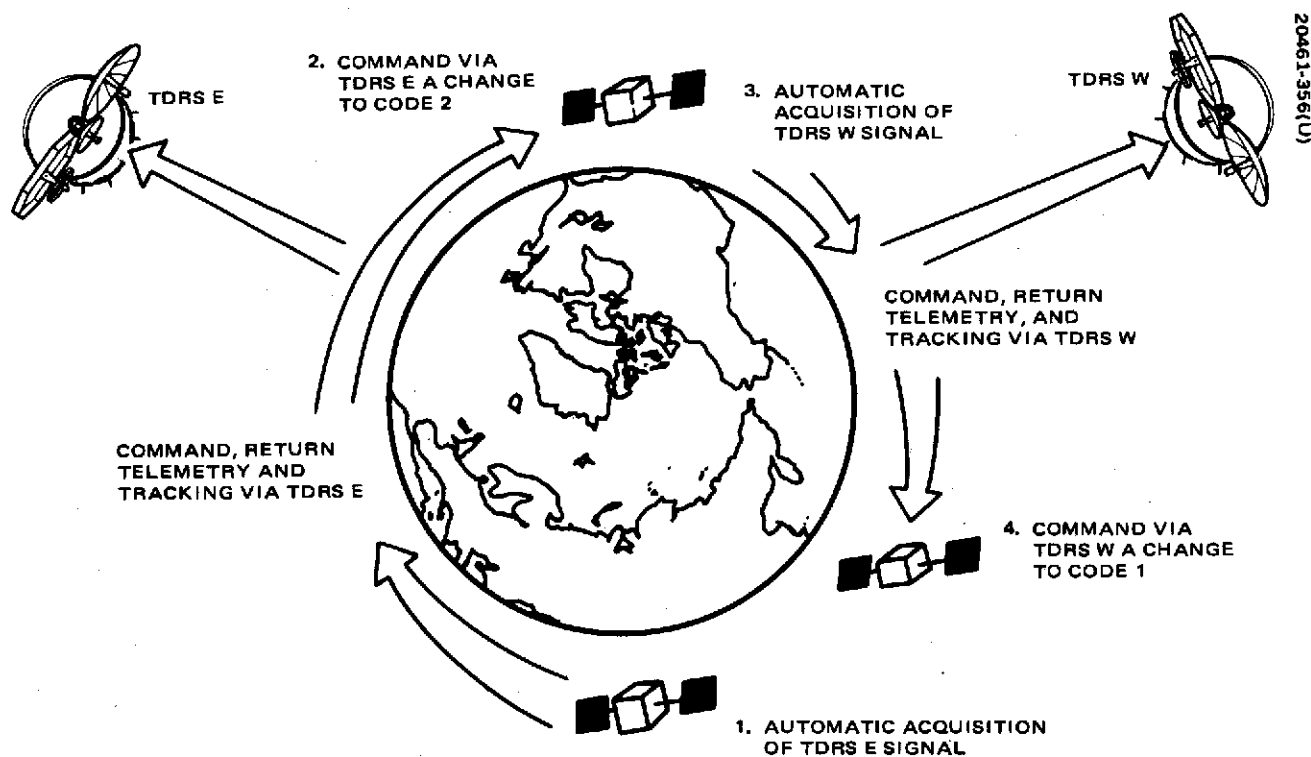


Figure 14. Low Data Rate Service Profile

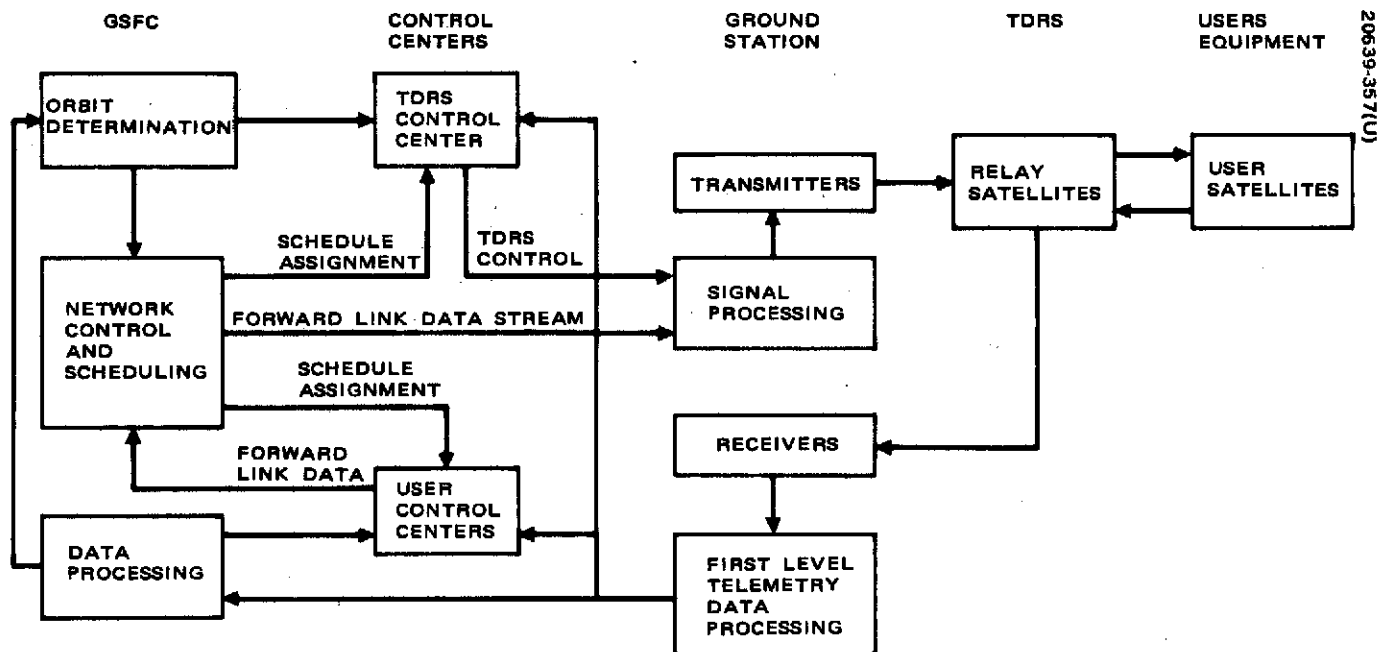


Figure 15. TDRSS Functional Operations

4.4 MDR SERVICE PROFILE

The operational sequence of events for establishing an MDR service two-way link with a user, listed in the following, is more straightforward than for the LDR service because only one user per TDRS is accommodated at a time. The sequence establishes antenna pointing and TDRS repeater frequency translation characteristics to allow communication.

- Scheduled service or priority override by S band order wire
- Set TDRS receiver and transmitter channels
- Point TDRS S band antenna at user by ground command
- Acquire signal and begin two way communication

4.5 TDRSS TELECOMMUNICATIONS SERVICE OPERATIONS

The major TDRSS operational elements are as follows:

- 1) GSFC Communication Control and Processing Facility
 - a) Telecommunication control and scheduling
 - b) Orbit determination
 - c) Data processing
- 2) Control centers
 - a) TDRS Control center
 - b) User control centers
- 3) TDRSS Ground Station
- 4) TDR satellites
- 5) TDRSS compatible users

The overall functional relationships between the operational elements are shown in Figure 15. The TDRSS link availability will be defined by the GSFC Scheduling and Control Facility, similar to the current NASA ground station scheduling, and will be forwarded to the users on a regular basis. Figure 16 shows additional details of the functional relationships between the ground elements. The TDRSS becomes an addition to current STDN capability and makes use of existing scheduling, switching, and data processing facilities at GSFC.

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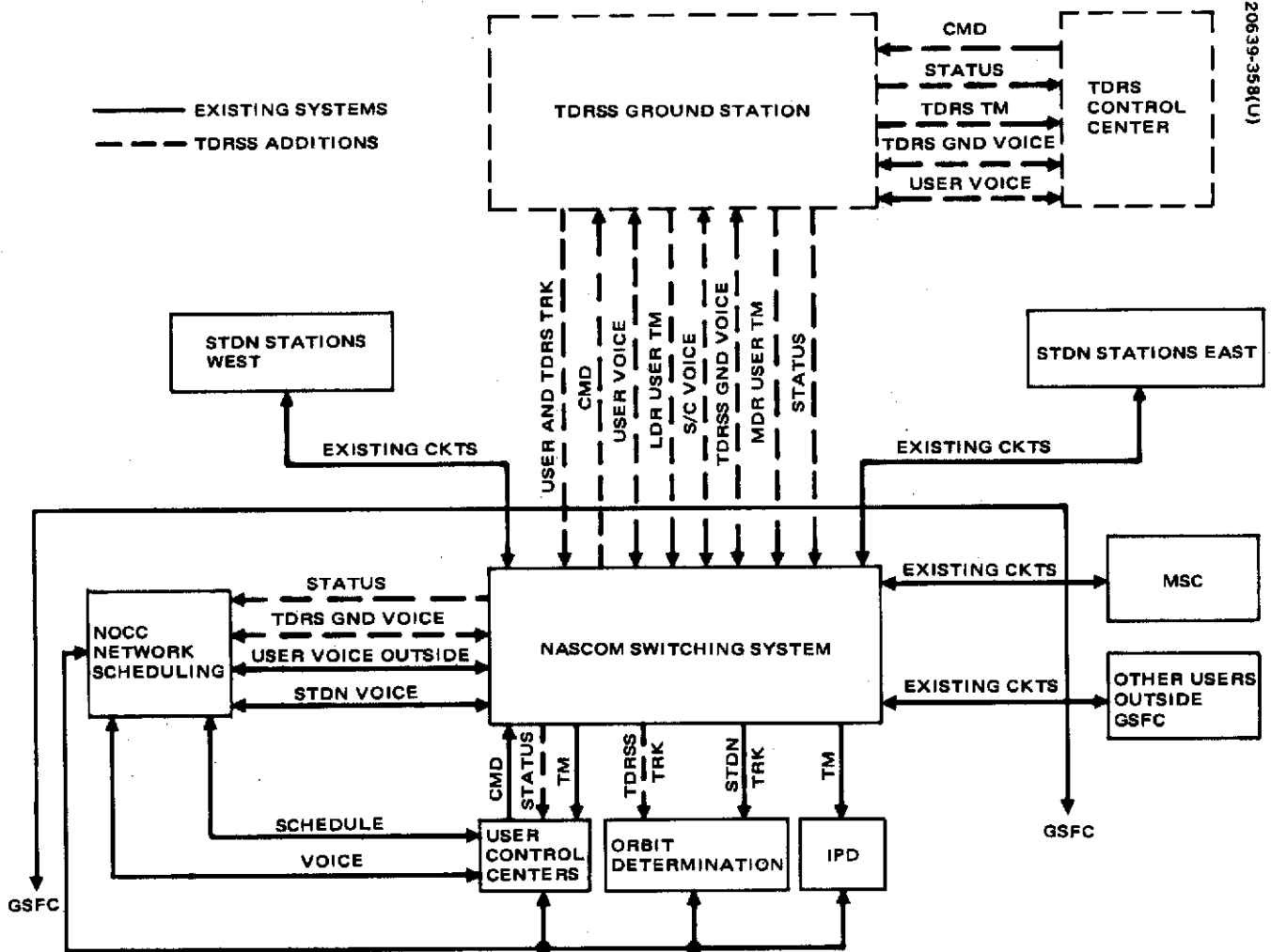


Figure 16. Relationship Between Ground Elements of TDRSS and Existing Facilities

During the scheduled times, the user spacecraft command data will be compiled at GSFC into a forward link data stream that will be sent to the TDRSS Ground Station for transmission to the user spacecraft.

The return link data are sent to GSFC where they can be routed directly to the user control center for processing. Orbit determination for both the TDRS and user satellites will be performed at GSFC. The user ephemerides will be made available to the user Program Offices and to the TDRSS Control Center, which is responsible for TDRS control.

A brief discussion of the individual elements and their operations is included in the following subsection.

4.5.1 GSFC TDRSS Operations

Most of the TDRSS operations at GSFC, shown in Figure 16, will utilize existing equipment and operational procedures. The network scheduling will be performed functionally in the same way as for the existing ground station networks. The schedule provided to the users and the TDRS control center will include the times that communication will be enabled and the relay satellite through which this communication will occur. As is the case with the present ground network, all groups involved will regulate their activities in accordance with these schedules. The various users will transmit their commands to a command processing operation at GSFC, which will assemble the forward link data stream in accordance with user requests, service capability, and priority assignments. This data stream will then be forwarded to the TDRSS Ground Station for transmission to the user satellites.

Telemetry data after a first level decommutation at the TDRSS Ground Station will be transmitted to the existing data processing facility at GSFC. As is the case with the present ground network, the processed data will be sent to the appropriate users, with TDRS data going to the TDRS control center. User and TDRS range and range rate data will be also utilized at GSFC for orbit determination.

4.5.2 TDRS Control Center

The TDRS Control Center will perform only those functions that are required to control and command the TDRSs. This includes the pointing of the MDR S band antenna and return ground link K band antenna, setting repeater channel gains and/or frequencies, east-west stationkeeping, and attitude maneuvers.

4.5.3 TDRSS Ground Station

4.5.3.1 TDRSS Ground Station Forward Link

The TDRSS ground station equipment interfaces with the GSFC communication processor via a high speed data line. The forward data stream is transmitted in real time at K band for relay to users by the TDRSs. A complete receiving and decoding system provides command verification

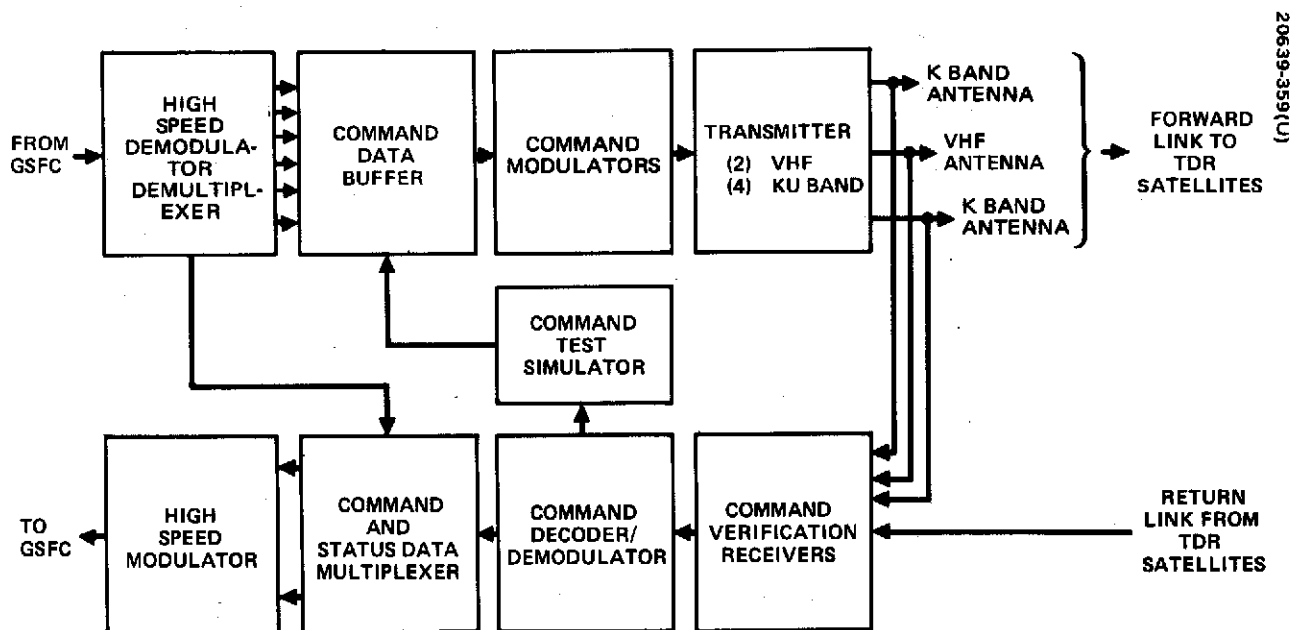


Figure 17. TDRSS Ground Station Forward Link

information to user operations control centers. A schematic of the forward link function is shown in Figure 17.

4.5.3.2 TDRSS Ground Station Return Link

LDR Return Link Functions. The return link functions are conceptually simpler than the forward link functions. Whereas the commands must be time multiplexed and transmitted sequentially to multiple user spacecraft, the return telemetry is code division multiplexed and received simultaneously, requiring parallel demodulation circuits. A schematic of the LDR return link functions is shown in Figure 18.

A signal from each TDRS, containing all return telemetry signals of visible user spacecraft, is separated from the other return links following amplification and frequency translation in the initial stages of the ground receiver. A data demodulator, set to a particular user's code, is connected to one of the two signals and performs the functions necessary to reproduce the return telemetry bit stream. In addition, the data demodulator outputs range and range rate measurements.

Telemetry data are transmitted to the GSFC data processing operations.

MDR Return Link Functions. The MDR return link functions, shown in Figure 19, are similar to those of the low data rate return link. However, there is only one user signal per TDRS being received and, hence, only two active demodulators are required at any time. If there is a variety of user signal forms, special demodulators may be required for each user.

4.5.4 TDRS Operations

The TDRS is, operationally, the simplest of all elements in that it acts only as a "bent pipe" that relays the signals received from the ground station to the user and relays the user signals to the ground station. The appropriate channel settings for MDR users and the required antenna pointing will be commanded from the TDRS Control Center.

4.5.5 User Telecommunications Terminal

To operate with the TDRSS, a user must supplement the NASA ground station compatible equipment with a TDRS compatible terminal and antennas as shown in Figure 20. These terminals can be connected with a switch to the regular command decoder and telemetry encoder. The choice between the ground station or TDRSS operation could be made any time during the user's mission by a simple command of the switch setting. The data and command rates for both modes of operation will likely be different; therefore, the transceiver includes an interface buffer unit.

The LDR users require a UHF and a VHF antenna. The VHF link to the TDRS is compatible in frequency with the user to ground station link. An MDR user requires an S band antenna.

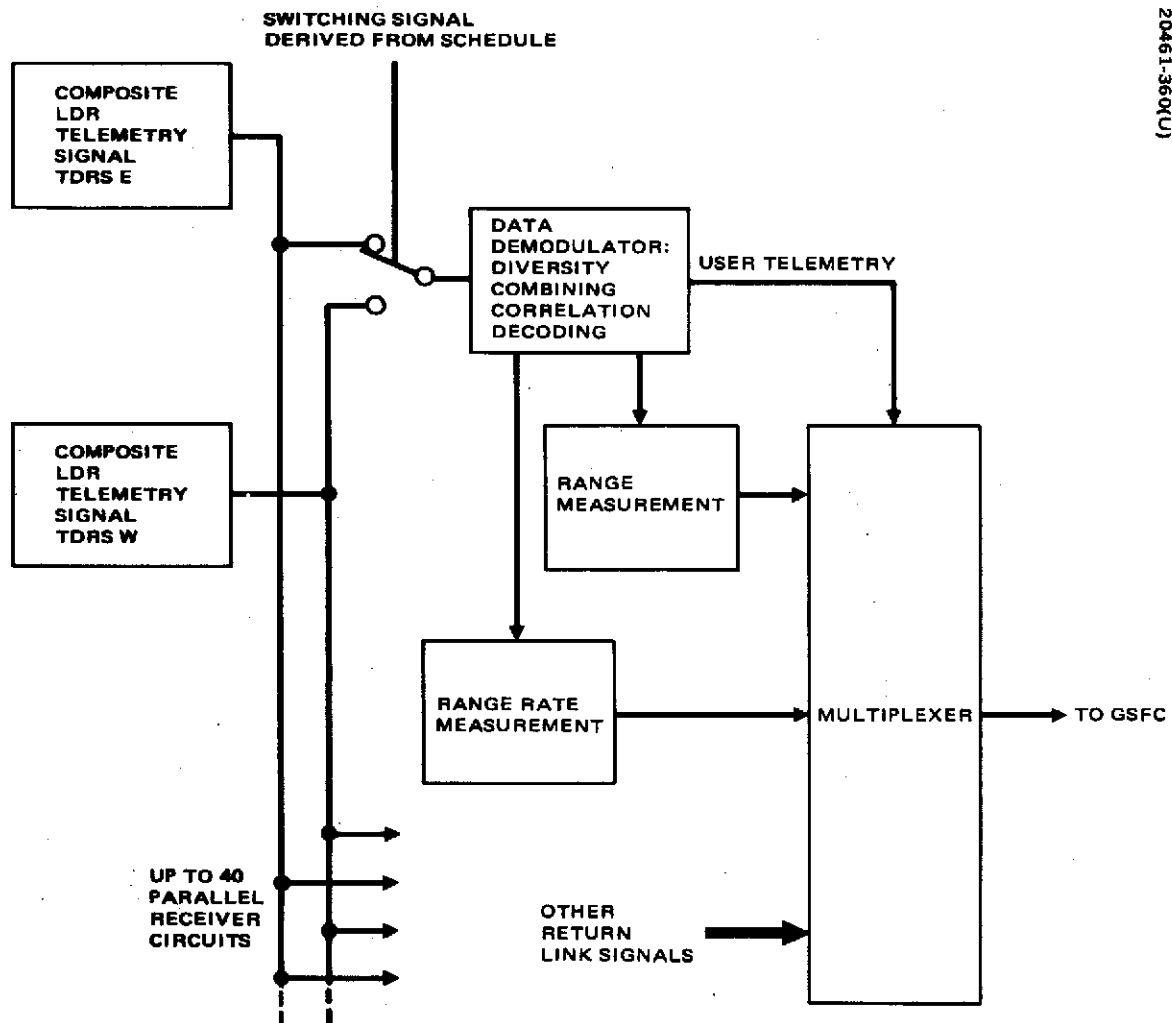


Figure 18. Ground Station Functions for Low Data Rate Return Link

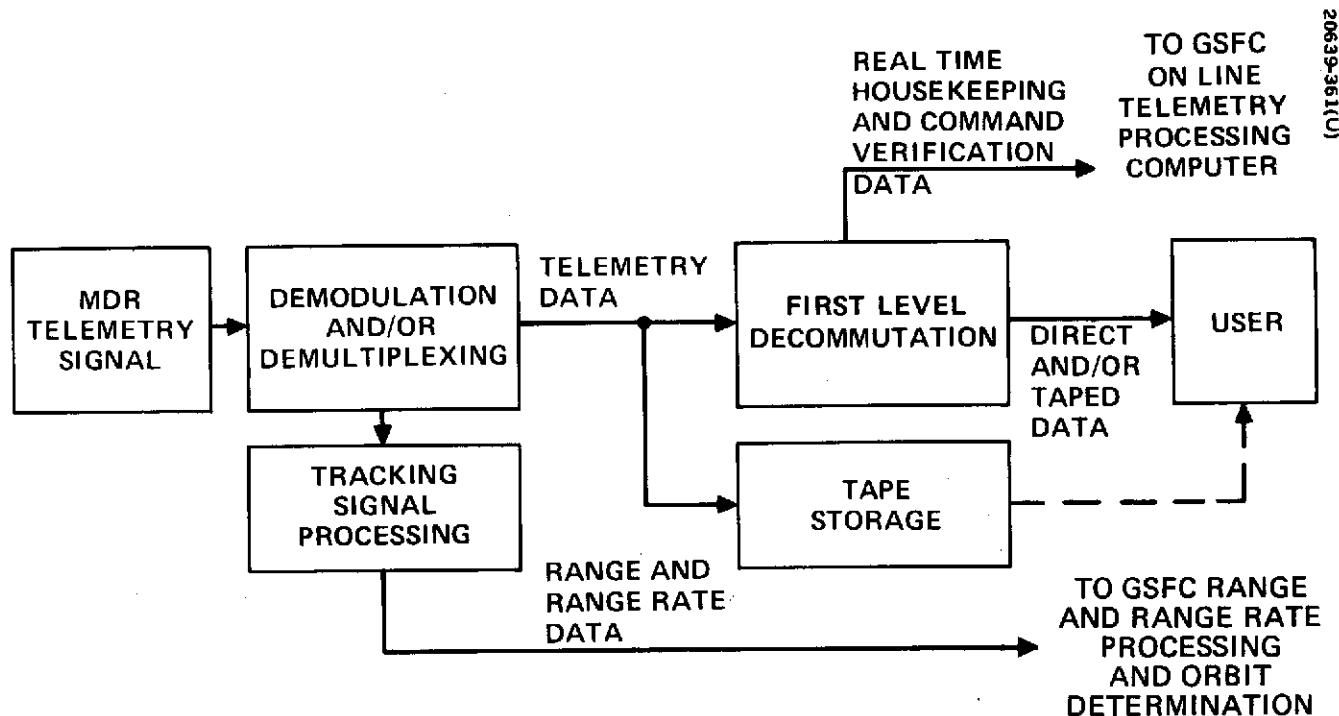


Figure 19. MDR Return Link Functions

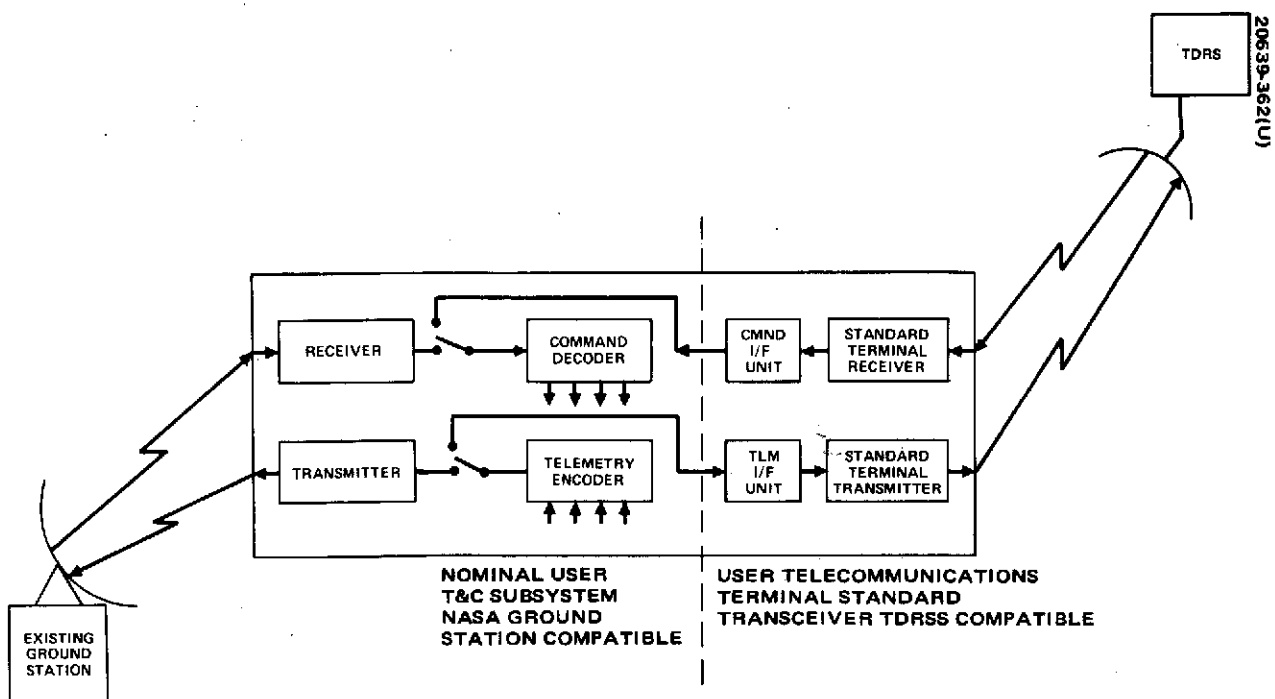


Figure 20. User Telecommunication Terminal

5. TDRS SYSTEM DESIGN

This discussion is divided into two subsections: 5.1 Telecommunication Service System and 5.2 TDR Spacecraft. The telecommunication service system discussion includes the ground facility, TDRS, and user equipment. The TDR spacecraft discussion includes an overview of the configuration, a mass estimate, and a power summary.

5.1 TELECOMMUNICATION SERVICE SYSTEM

The TDRSS telecommunication service system comprises four major elements:

- TDRS telecommunication subsystem
- TDRSS user equipment
- TDRS Ground Station
- GSFC facilities for network scheduling and control, orbit determination, and data processing.

The first three elements will be briefly discussed in the following sections, whereas the GSFC facilities will not be discussed in this report.

5.1.1 TDRS Telecommunication Subsystem

The telecommunication subsystem shown in Figure 21 interfaces with the ground station at K band and with the users both in the VHF/UHF bands and S band. Interface is maintained between the earth and TDRS with a K band link. UHF and VHF are used to communicate with low data rate users and S band is used to communicate with medium data rate users. The K band receivers simultaneously receive four different carrier frequencies. These carrier frequencies are shifted to a low IF, amplified, and divided in a power divider to the various points of data reception within the TDRS.

The TDRS VHF/UHF subsystem transmits voice and commands at UHF. The UHF transmitter utilizes solid-state power amplifiers for reliability, mass efficiency, and flexibility. The transmitter has a high power mode to permit simultaneous voice and command. The VHF antenna/receiver

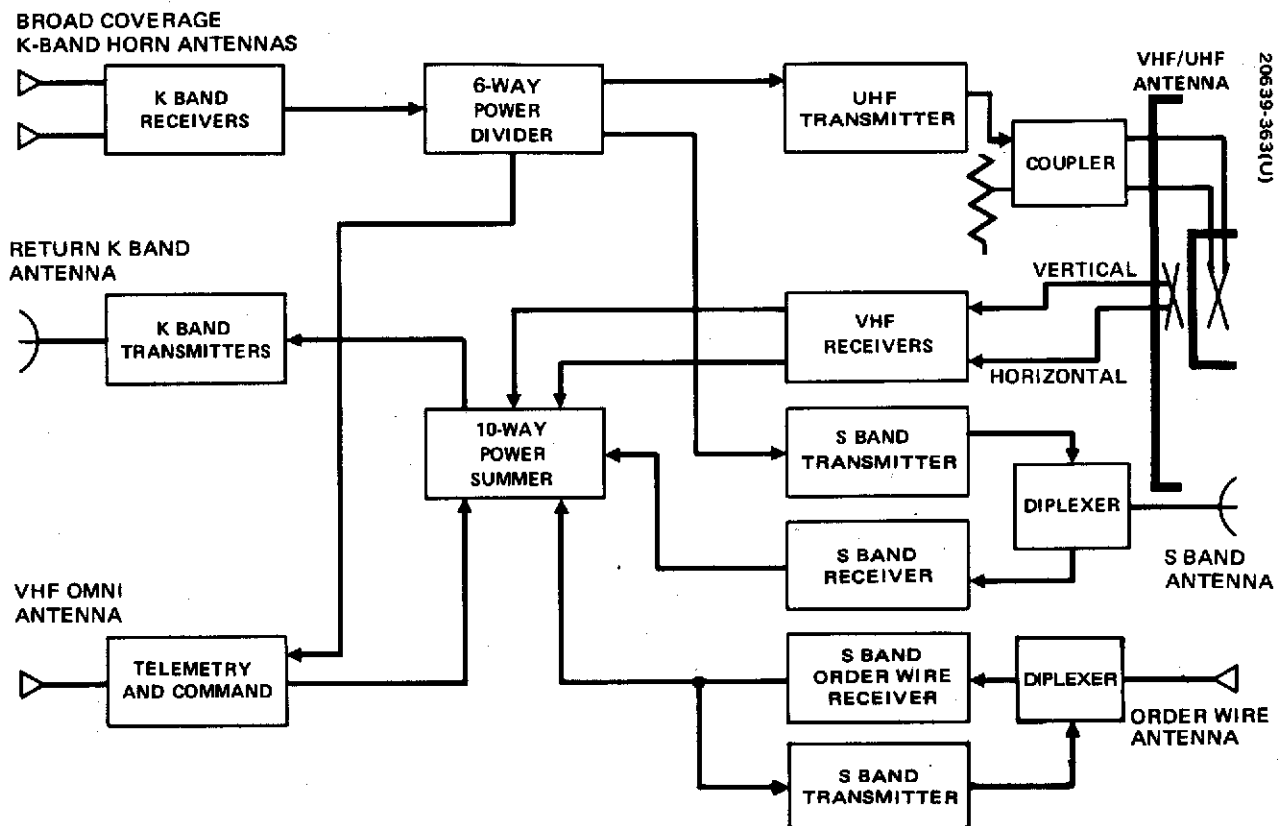


Figure 21. TDRS Telecommunication Subsystem

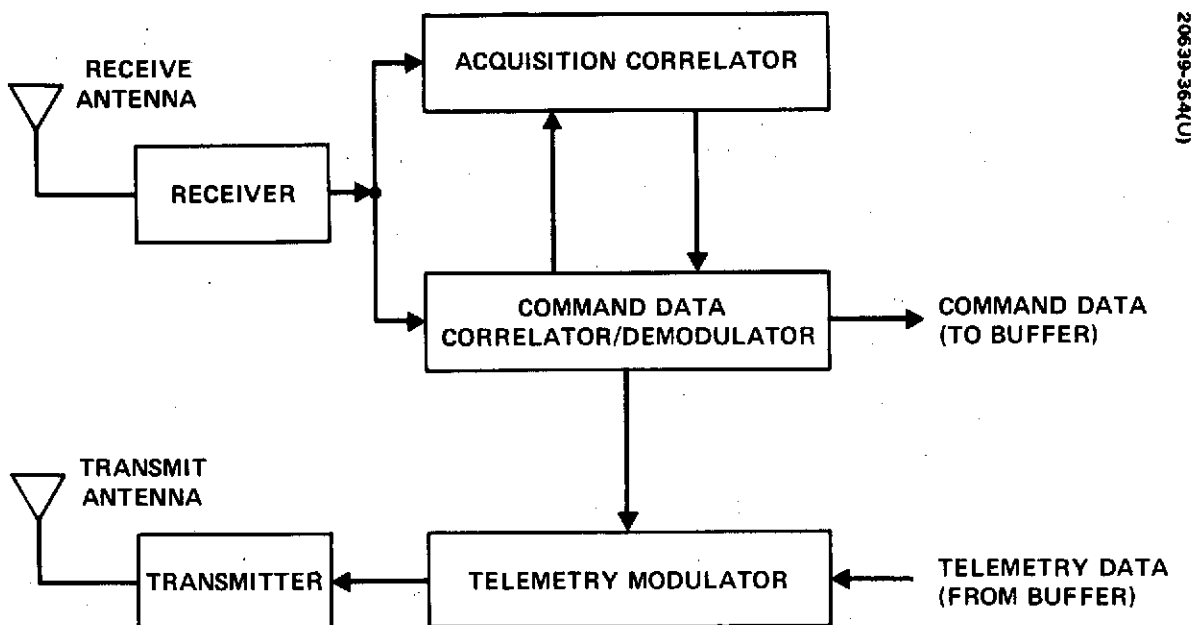


Figure 22. TDRSS User Equipment (Transceiver)

configuration resolves incoming signals into vertical and horizontal components, which are returned to the ground separately. The receivers can accept at least 20 telemetry users and one voice user simultaneously.

The TDRS S band system transmits at 10 MHz within the 2035 to 2120 MHz band. A single user is serviced by the S band transmitter and receiver. The receiver operates in the 2200 to 2300 MHz band. As in the case of the transmitter, the receiver may be tuned in 1 MHz steps. The S band transmitter has a 10 MHz bandwidth. Thus, the S band system is capable of operating at any frequency within the assigned frequency bands and, in effect, provides a "bent-pipe" system.

In addition to the S band transmitter and receiver for data transmission and reception, there is an S band order wire receiver and S band transponder. The order wire receiver uses an earth coverage beam antenna and is capable of receiving any user in near earth orbit. The purpose of the order wire receiver is to provide an emergency channel from a user spacecraft through the TDRS to the ground control.

The transponder receives 8 MHz centered at 2290 MHz and retransmits this band centered at 2045 MHz; this allows trilateral ranging.

Voice capability is provided by both the UHF transmitter and the S band transmitter. In both cases a push-to-talk feature is employed.

A backup telemetry and command subsystem is provided for the main K band telemetry channel. The VHF telemetry receivers are on continuously, while only one of the K band receivers is on at a given time.

5.1.2 TDRSS User Equipment (Transceiver)

The TDRSS user UHF/VHF receiving/transmitting equipment (transceiver) consists of the following major components, interrelated as shown in Figure 22: antenna, receiver, signal acquisition matched filter correlator, command data correlator, telemetry modulator, transmitter, and interface buffers.

The acquisition correlator permits rapid forward link signal acquisition and provides pseudo noise (PN) code timing to the command correlator, which maintains pattern and frequency lock after initial acquisition. The acquisition correlator is disabled after the data correlator achieves lock.

The telemetry transmitter frequency may be phase locked to the received frequency for two-way, coherent tracking, but may be allowed to run free during telemetry data transmission, enabling handover between TDRS without interrupting data flow. The transmit PN generator can similarly be synchronized to the receive PN generator so as to provide two-way "turn-around" ranging.

No processing other than modulation/demodulation is performed within the TDRS repeater. The command data are delivered to the user

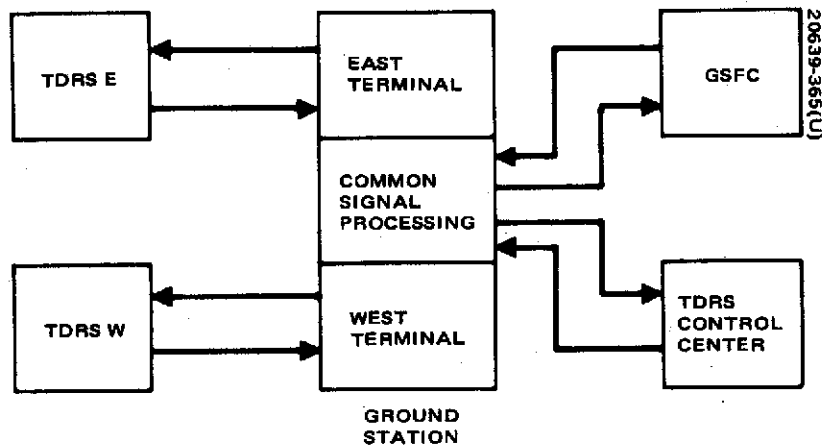


Figure 23. Ground Station Concept and External Interfaces

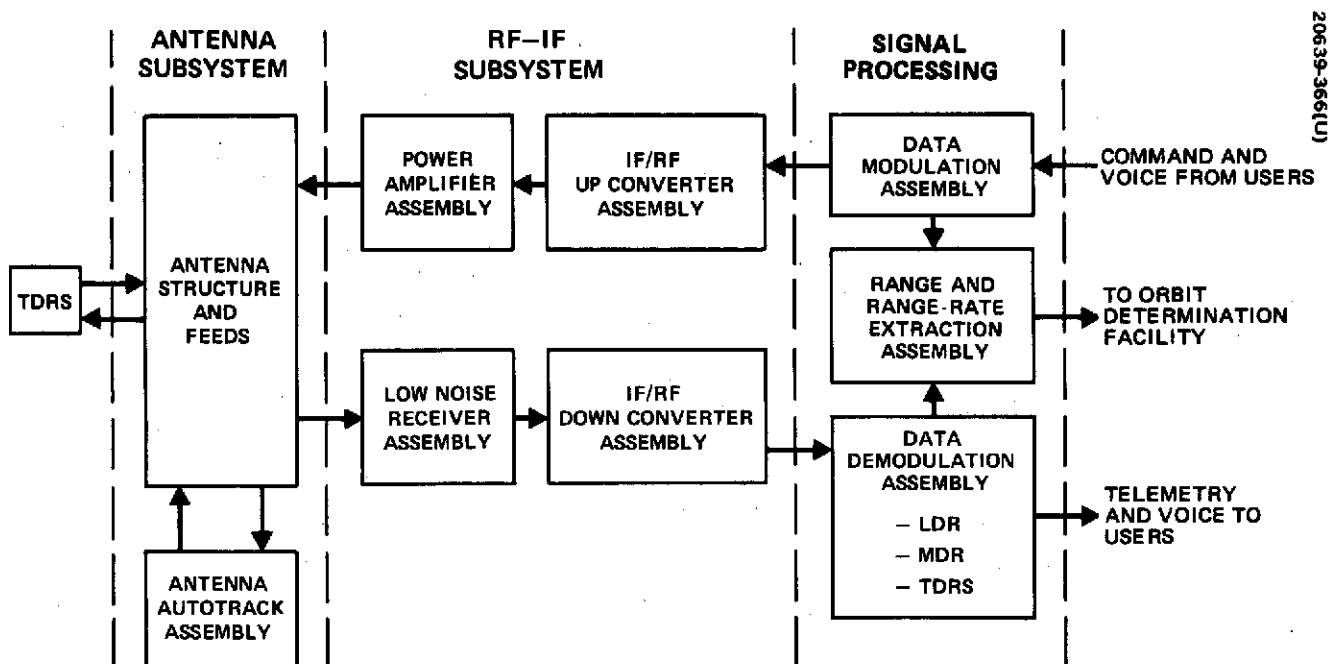


Figure 24. Ground Station Configuration

spacecraft simply as a clocked bit stream. Estimated characteristics of the LDR transceiver, including a 5 watt transmitter, are as follows:

- | | |
|--------------|--|
| 1) Mass | 11 kg (24 pounds) |
| 2) Bus power | 25 watts |
| 3) Volume | 0.14 m ³ (0.5 ft ³) |

5.1.3 Ground Station

The ground station is the interface element between the TDR spacecraft and the two control centers — GSFC and the TDRS control center. The general relationship of the ground station to these other elements is shown in Figure 23. Also shown in this figure are the three major portions of the ground station: 1) a terminal for maintaining RF communication with TDRS E, 2) a terminal for maintaining RF communication with TDRS W, and 3) a common area containing demodulation and processing equipment, which will be applied to signals from both terminals.

The RF terminals are of conventional design, but the signal demodulation and processing equipment, although not new in concept, has not been previously applied in the complexity required for simultaneous multiple user communication via the TDRSS.

A third terminal may be required for communication with the in-orbit spare TDRS and for redundancy. This will require only a slight increase in the processing equipment and its configuration controls.

The terminals consist of five major portions: 1) the antenna structure, 2) the antenna tracking subsystem, 3) the K band RF/IF subsystem, 4) the VHF backup system, and 5) the TDRS tracking antenna. Figure 24 shows schematically how this equipment is arranged for each TDRS.

The antenna subsystem operates at both K band and VHF with a 12.8 meter (42 feet) diameter dish. The K band antenna is a Cassegrain type, while the VHF configuration utilizes a focus feed design. The tracking assembly consists of a pair of tunnel diode preamplifiers, tracking comparator, and an antenna controller unit.

The RF/IF subsystem for each terminal includes two power amplifiers at K band for transmission of the voice, LDR, MDR, TDRS command, and TDRS beacon signals. The receiver assembly includes a low noise parametric amplifier mounted on the antenna structure.

The signal processing subsystem consists of the equipment required for data modulation and demodulation and for extraction of doppler and ranging information. The equipment processing the MDR and TDRS data is of conventional design, but the LDR equipment requires state of the art design and technology. The LDR equipment includes acquisition correlators, telemetry correlators for actual PN/PSK demodulation, polarization diversity combiners,

and error correction decoders. Notch filter units are also provided for RFI rejection.

5.2 TDR SPACECRAFT

5.2.1 Configuration

The TDR is a Gyrostat configuration (shown in Figure 25), designed for compatibility with a Delta 2914 launch vehicle. The maximum payload capability into the elliptical transfer orbit is 680.4 kg (1500 pounds). An apogee motor injects the spacecraft into synchronous orbit. Hydrazine propulsion is provided for spin axis attitude control and orbital maneuvers. Power is generated by solar cells, and batteries are provided for eclipse operation.

The spinning section supports and houses the propulsion, electrical power, attitude control, and some of the telemetry and command equipment. The apogee motor is installed in the central thrust tube. Hydrazine tanks are mounted on ribs extending from the thrust tube to the solar cell array. Batteries, battery controllers, despin control electronics, and telemetry, and command equipment are mounted on the ribs and small equipment platforms spanning the ribs. The aft end of the spinning section is sealed by means of a thermal barrier which protects the spacecraft equipment during apogee motor firing and minimizes heat loss during orbital operations. Attitude control sensors, radial control jets, and umbilical connectors are installed in a cell array. The axial jets are mounted on truss supports and protrude through the aft thermal barrier. The VHF omni antenna is mounted on the aft closure of the solar cell array.

A despun section houses the communication equipment and some of the telemetry and command equipment. Electronic equipment is mounted on a thermally controlled platform. Antennas are mounted off the platform on a mast support structure. Short backfire-type antennas are provided for the LDR user VHF return link and the UHF forward link. A parabolic reflector antenna is provided for both forward and return link S band service for the MDR user. These antennas are folded and stowed within the payload fairing during launch. The TDRS-to-ground link at Ku band incorporates a high gain parabolic reflector antenna. This antenna is secured to absorb launch loads. Both the S band and Ku band paraboloid antennas are installed on two axis gimbals, and an S band short backfire antenna is provided for the ground-to-TDRS and order wire service.

5.2.2 Mass Estimate

During the design, considerable attention has been devoted to minimizing the spacecraft mass: an orbital inclination of 7 degrees has been chosen, a high performance apogee motor has been selected, low mass antenna designs have been obtained from Radiation Incorporated, and considerable use of beryllium has been made in the spacecraft structural design.

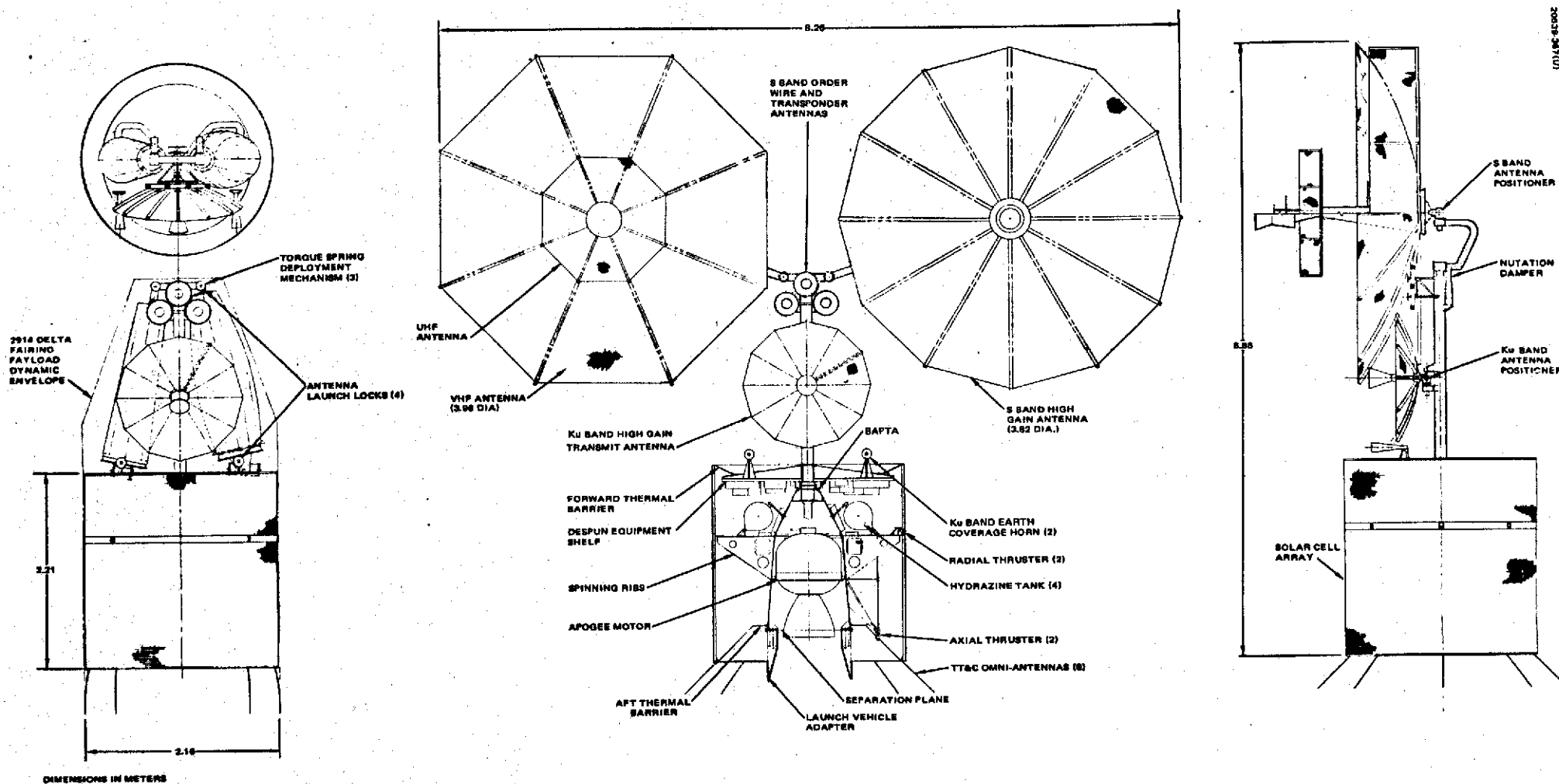


Figure 25. TDRS Configuration

With such a design approach the current mass estimate shows a contingency of 25.6 kg. Since many of the subsystems have been configured with flight proven components and technology; this mass contingency is deemed adequate.

A subsystem mass breakdown is shown in Table 3.

TABLE 3. TDRSS MASS SUMMARY

Subsystem/Item	Mass, kg
Repeater	55.1
Telemetry and command	18.1
Antennas	36.6
Attitude control	23.5
Reaction control (less propellant)	11.4
Electrical power	61.5
Wire harness	11.5
Apogee meters (burned out)	25.5
Structure	68.2
Thermal control	10.0
Contingency	25.6
Final weight in orbit	347.0
Hydrazine propellant*	38.0
Initial weight in orbit	385.0
Apogee motor expendables*	293.0
Separation weight**	678.0

*Propellant provided for full launch vehicle capability.

**Perigee plane change maneuver decreases mass by 2.4 kg.

5.2.3 Electric Power Summary

The solar array is designed to provide all the energy required by the spacecraft loads, including battery charging. The TDRS power summaries for several modes of operation are shown in Table 4.

The power demand for voice transmission exceeds the solar cell array capability. This power demand is considered to be intermittent and can be supported 25 percent of the time at UHF (50 percent of the time at S band for the same level of power) with some battery augmentation. The battery charging power is sufficient to provide for both the eclipse loads and the battery augmentation loads.

TABLE 4. TDRSS ELECTRIC POWER SUMMARY

Summer Solstice			
Mode	Command	Intermittent S Band Voice	Intermittent UHF/VHF Voice
Power Source	Solar at 27.5 Volts	Solar at 27.5 Volts	Solar and Battery at 25.5 Volts
Percent operating time	50 to 75*	50*	25*
Frequency Synthesizer	8.0	8.0	7.4
K band equipment	36.0	36.0	33.5
UHF/VHF equipment command and data	157.8	157.8	146.1
UHF Voice	—	—	142.0
S band equipment command data voice	24.0	—	22.2
S band Voice	—	96.3	—
Telemetry equipment	15.6	15.6	14.5
Antenna position control	6.0	6.0	6.0
Despin control	19.7	19.7	18.3
Thermal control	5.6	5.6	4.6
Power electronics	14.8	11.0	30.0
Battery charging	37.5	—	—
Distribution losses	8.0	8.0	9.0
Reserve power	31.0	—	—
Power available or required	364.0	364.0	433.6

*Either the UHF or the S band voice transmitter operates but not both simultaneously.

Table 4 (continued)

Eclipse Season

Mode	Command	Intermittent S Band Voice	Intermittent UHF/VHF Voice	Command	Intermittent S Band Voice	Intermittent UHF/VHF Voice
Illumination	Sunlight			None		
Power Source	Solar at 27.5 Volts	Solar at 27.5 Volts	Solar and Battery at 25.5 Volts	Battery at 25.5 Volts	Battery at 25.5 Volts	Battery at 25.5 Volts
Percent operating time	50 to 75*	50*	25*	50 to 75*	50*	25*
Frequency Synthesizer	8.0	8.0	7.4	7.4	7.4	7.4
K band equipment	36.0	36.0	33.5	33.5	33.5	33.5
UHF/VHF equipment command and data	157.8	157.8	146.1	146.1	146.1	146.1
UHF voice	—	—	142.0	—	—	142.0
S band equipment command data voice	24.0	—	22.2	22.2	—	22.2
S band voice	—	96.3	—	—	89.5	—
Telemetry equipment	15.6	15.6	14.5	14.5	14.5	14.5
Antenna position control	6.0	6.0	6.0	6.0	6.0	6.0
Despin control	19.7	19.7	18.3	18.3	18.3	18.3
Thermal control	5.6	5.6	4.6	4.6	4.6	4.6
Power electronics	18.0	11.0	20.0	40.0	45.0	50.0
Battery charging	60.0	—	—	—	—	—
Distribution losses	8.0	8.0	9.0	20.8	8.0	9.0
Reserve power	40.3	35.0	—	—	—	—
Power requirements**	399.0	399.0	416.4	292.2	359.5	453.6

*Either the UHF or the S band voice transmitter, operates but not both simultaneously.

**Minimum power available during eclipse season is 399 watts.

6. TDRS SYSTEM RELIABILITY

6.1 OPTIMUM TDRS MASS/RELIABILITY TRADEOFF

The satellite mass/reliability tradeoff has been investigated with a computer program that optimizes the satellite reliability as a function of design mass. Although in principle, reliability can be increased to any desired level with the incorporation of additional subsystem redundancy, in practice the mass penalties associated with redundancy of some subsystem units are prohibitive. For this reason the upper limit on reliability for a practical satellite design is considerably less than 1.0 for typical mission lifetimes. The mass/reliability tradeoff illustrating variations to the baseline design is shown in Figure 26. The reliability numbers include only those failures in the satellite once it is initially deployed. The estimated reliability for satellite launch and deployment is 0.944 (see subsection 3.4.1.3 of Volume 5).

Figure 26 shows that the practical upper limit on satellite reliability is about 0.9, even if a large increase in launch booster capability was available. The selection of the present baseline design is dictated primarily by the size of the desired contingency. The baseline design is not on the optimum mass/reliability curve because the design within the various subsystems is not exactly that which is given by the analysis. This deviation from the analytical optimum represents a mass penalty of about 2 kg. The satellite reliability is shown as a function of lifetime in Figure 27. The mean-times-to-failure (MTTF) for the baseline design is 7.7 years.

The reliability numbers quoted require that the satellite be fully operational in all aspects. It should also be noted that many failure modes result only in a partial reduction of service, and will not seriously detract from the utility of the system. For instance, the failure of one LDR forward link does not disable the return link; in such a case, the system performance would be degraded only by the requirement that all LDR user commands must be transmitted through the other TDRS. Furthermore, the LDR links may fail completely but this does not reduce the MDR service. Other subsystem malfunctions which have been classified as failures (e.g., shorting of three cells in one battery) may only reduce future reliability (i.e., battery lifetime due to higher depth of discharge).

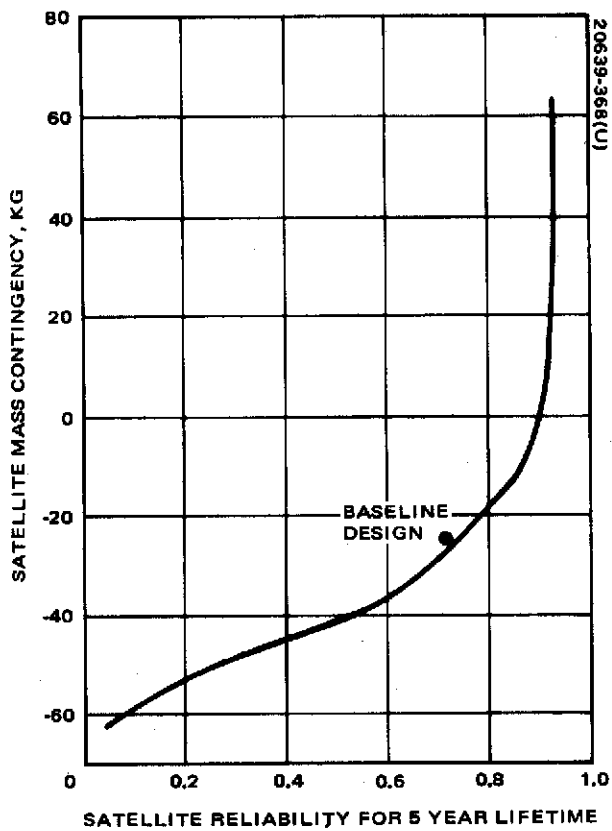


Figure 26. Optimum TDRS Mass/Reliability Tradeoff

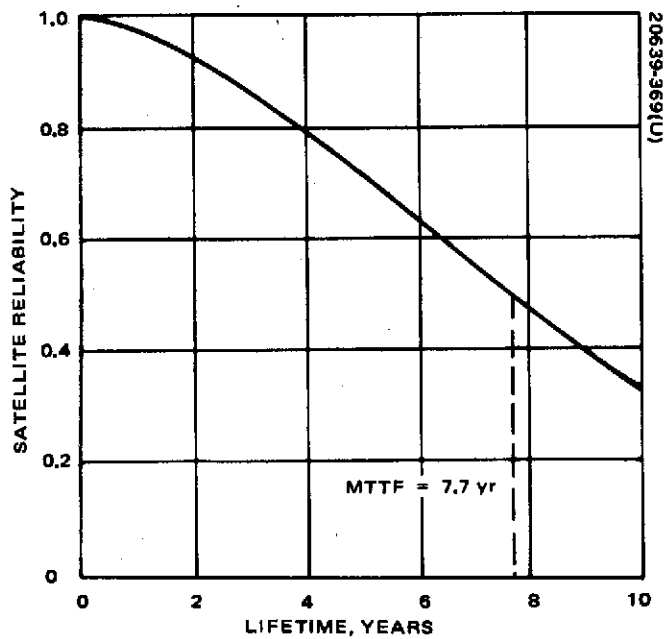


Figure 27. Baseline Design Satellite Reliability

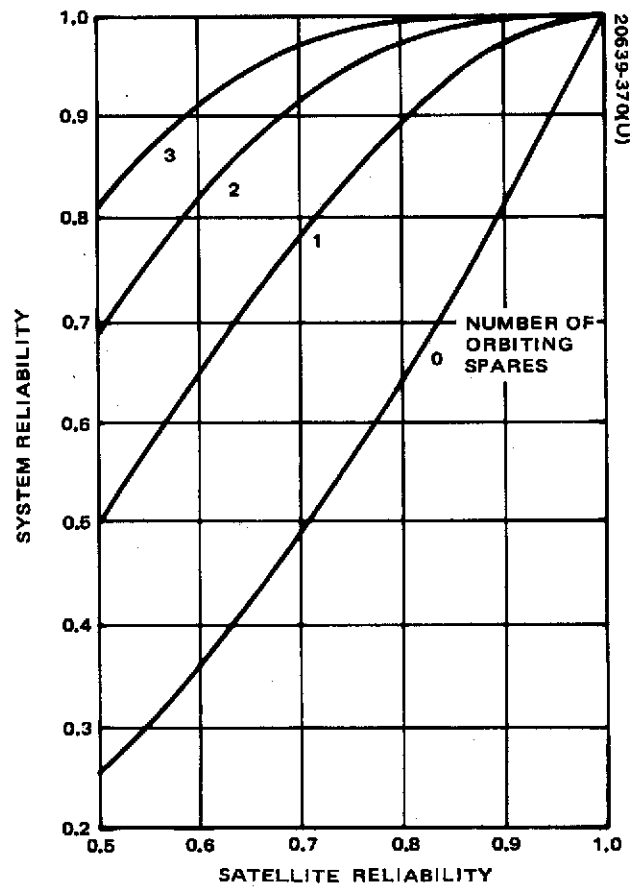


Figure 28. Reliability for Two-Satellite System

Since the probability of successful launch and deployment is estimated at 0.944, it follows that 1.059 total launches will be required for each launch, leading to a successful injection and deployment of the satellite. For purposes of cost estimation, it is possible to utilize a non interger number of launches. There is of course no way to foretell whether or not the TDRS program will be "lucky" in the area of launch failures. The subsequent discussions of system reliability presume that enough launches are made to obtain the stated satellite deployment since launch and deployment failures are most conveniently handled separately.

6.2 OPERATIONAL TDRSS RELIABILITY

The TDRSS is considered fully operational when two fully operational TDRSs are available to provide user service. The system reliability depends not only upon the satellite reliability, but also on the number of spares allocated for replacement of failed satellites. Figure 28 shows the system reliability as a function of the satellite reliability and the number of orbiting spares (the satellite design). Figure 28 shows that the shape of the reliability curve for a system with no orbiting spares is significantly different from systems utilizing orbiting spares. The no spare system has relatively low values of system reliability even when the satellite reliability is high; therefore, any practical system operational concept must include at least one orbiting spare.

6.2.1 Operational TDRSS Without Replacement of Failed TDR Satellites

One alternative for operational TDRSS operations is to initially deploy the system (including orbiting spares) and to then let the system "run down" by not launching replacements for failed satellites. For this case, the system reliability can be computed directly from Figures 27 and 28. A system utilizing one initially orbiting spare appears to be a reasonable choice. For this system we note from Figure 28 that the MTTF (reliability = 0.5) happens to be identical for the satellite and the system. TDRSS MTTF is then that shown in Figure 27 (i. e., 7.7 years for the baseline design).

6.2.2 Operational TDRSS With Replacement of Failed TDR Satellites

One alternative for operational TDRSS operations is to maintain the system by launching replacement spacecraft as the TDRS fail. A reasonable operational strategy would be to maintain one orbital spare satellite, which is replaced as soon as possible after a TDRS failure. If this replacement can be made within 3 months of the failure, the TDRSS will be fully operational 99.7 percent of the time. This maintenance requires an average of 0.41 launch per year (including launch and deployment failures) for the baseline satellite design. As noted previously, the TDRSS will be useful most of the time that it is not fully operational.

A system utilizing two orbiting spares would increase the required launches by a factor of 4/3, but would be fully operational 99.98 percent of the time.